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Outdoor Temperature and Indoor Thermal Comfort: Raising the Precision of the Relationship for the 1998 ASHRAE Database of Field Studies

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ABSTRACT

Relations between indoor neutral temperatures and outdoor temperatures are currently proposed as an "adaptive standard" to supplement ASHRAE Standard 55-1992. They rest on the 1998 ASHRAE database. Humphreys and Nicol drew attention to the depression of the regression coefficient by measurement and formulaic error in thermal comfort indices. This paper applies their suggested correction, and improves the precision of the relations. Comparison is made with similar relations from earlier data. The relation for unheated, naturally ventilated buildings has remained unchanged. The form of the relation for the HVAC and heated buildings has remained similar. However, the neutral temperatures in the new data were about 2°C higher where the outdoor temperature is in the region of 0°C. The outdoor mean air temperature is as satisfactory as Effective Temperature (ET) as a statistical predictor of the indoor neutral temperatures. These findings confirm the stable basis of the proposed adaptive standards.*

INTRODUCTION

A database of thermal comfort field studies from 160 buildings in various countries and climates has been assembled for ASHRAE (de Dear 1998). The database consists of over 20,000 individual observations of thermal comfort (comfort votes), mostly from office workers, with concurrent measurements of their thermal environment. Appended to the observations are the calculated values of various indices of thermal comfort. Three types of building are distinguished: centrally air-conditioned (HVAC), mixed mode (MM), and naturally ventilated (NV).

de Dear and Brager (1998) have analyzed the data. Among the relationships they explored was the link between the indoor Operative Temperature required for thermal comfort, and the outdoor daily average shade Effective Temperature (*ET**). They estimated these relations both for naturally ventilated buildings and for those with centrally controlled air conditioning. These relations are proposed as a basis for an "Adaptive Comfort Standard" to supplement the current ASHRAE Standard 55-1992 (ASHRAE 1992). The relations are therefore likely to be of considerable practical importance, both for the design of naturally ventilated buildings and for the sizing and operation of HVAC systems.

Humphreys and Nicol (2000) explore the effects of measurement errors and formulation errors on the statistical behavior of thermal comfort indices. They show, using examples from the ASHRAE database, that regression coefficients can, in some circumstances, be seriously depressed by these kinds of error. They suggest an adjusted regression coefficient to compensate for this effect. This paper explores to what extent the relationship between the outdoor temperature and comfort indoors can be "sharpened up" by applying this adjusted regression coefficient to the derivation of the temperatures for thermal neutrality.

ESTIMATING A NEUTRAL TEMPERATURE

The application of regression analysis to thermal comfort data goes back at least to Bedford (1936) and has been the usual procedure for obtaining the neutral temperature from a batch of field study observations. The procedure estimates a linear regression equation of the form:

$$y = a + b(x). \quad (1)$$

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The regressor (or independent) variable (x) is an index of the thermal environment, and the response (or dependent) variable (y) is the comfort vote, usually on the seven-point ASHRAE scale (cold [−3], cool [−2], slightly cool [−1], neutral [0], slightly warm [1], warm [2], hot [3]). The gradient (b) is the regression coefficient, and the constant (a) is the vertical intercept. The statistics (a) and (b) are estimated from the data, and the equation is then solved to obtain the temperature at which the mean vote would have been zero (neutral). If, however, the regression coefficient (b) has been depressed by the action of measurement and formulaic error in the regressor, an incorrect estimate of the neutral temperature will result. Hitherto in the analysis of thermal comfort field study, this effect has been overlooked.

de Dear and Brager (1998) used regression analysis to estimate neutral temperatures in terms of the Operative Temperature, taken to be the mean of the air temperature and the radiant temperature. They treated separately the data from each building in the database. Independent analysis of the data from each building is good practice because the thermal environment differed from building to building and the occupants may have become adapted to these different conditions by, for example, choosing different weights of clothing.

The decision to treat the buildings separately meant that some batches of data had fewer responses than might have been desired. There are likely to be enough observations, even in a quite small batch of data, to give adequate practical accuracy to the mean value of the comfort vote and to the mean value of the room Operative Temperature. However, a reasonably precise estimate of the regression coefficient requires many observations, unless the correlation between the comfort vote and temperature is high. de Dear and Brager overcame this difficulty by excluding from further analysis those buildings from which the regression equation was not statistically significant at the 5% level of confidence. Of the 160 buildings, over one-third failed the test. The neutral temperatures from these buildings are, unfortunately, lost to further analysis.

A further difficulty is a by-product of the rapidity of automated data collection. A researcher using one set of equipment can collect in a single working day many sets of observations of thermal comfort, together with comprehensive measurements of the thermal environments of the respondents. So the results of a small survey sometimes represent a single visit to the building or perhaps visits over only two or three days. The measured thermal environments are, therefore, not necessarily typical of those experienced by the respondents. They might represent unusually hot or cold days, or the thermal environment might be a product of a temporary malfunction of the heating or cooling system.

People tend to become well adapted to their normal conditions. Before the advent of automation, surveys often took a month or more to complete. Consequently, the mean comfort vote from a protracted survey was fairly representative of the normal experience of the occupants and, therefore, usually close to thermal neutrality. A survey on a single day is, however, quite likely to produce a mean comfort vote substantially different from neutral. This makes the estimate of the neutral temperature from the regression equation more sensitive to any uncertainty in the value of the regression coefficient —and smaller batches of data typically yield less certain regression coefficients.

CORRECTING THE REGRESSION COEFFICIENT FOR THE EFFECTS OF ERROR IN THE INDEX

A matter to which attention has recently been drawn is that the regression coefficient, even if precisely evaluated, is likely to be misleading if it is taken to indicate the true dependence of the mean comfort vote on the thermal index. In the presence of measurement errors in the variables contributing to the thermal index, or of approximation in its formulation, such as the omission of relevant variables, the regression coefficient is underestimated. Humphreys and Nicol (2000), in a companion paper, explore this effect with particular reference to the ASHRAE database.

Operative Temperature is not subject to large measurement errors, but it is subject to formulaic error because of its omission of the effects of variations of humidity, air movement, clothing insulation, metabolic rate, etc. The variations of these omitted variables tend to "dilute" the regression and lower the coefficient. There is no physical reason to suppose that the true regression coefficient for people not far from thermal neutrality should, apart from the effect of this scatter, vary systematically from building to building within the database. From a consideration of the values obtained in the database, Humphreys and Nicol (2000) argue that this true value is approximately 0.5 scale units/K. While a more precise estimate would be desirable, they point out that using even this approximate value would improve the estimates of the neutral temperature from the regression equations.

This adjusted coefficient has been used to recalculate the neutral temperatures from the database. One batch of data was excluded because the mean of the ASHRAE vote lay beyond the range ±2. For the majority of the buildings, the two calculations gave an almost identical value for the neutral temperature. The larger differences occur only if the mean comfort vote differs greatly from zero and the unadjusted regression coefficient differs greatly from 0.5.

RECALCULATING DEPENDENCE ON OUTDOOR TEMPERATURE

Applying the correction for the effect of the formulaic and measurement errors in the Operative Temperature affords the possibility that the relations in the database that depend on neutral temperatures could be made more precise. Among them is the relation between the indoor neutral Operative Temperature and the outdoor temperature.

de Dear and Brager calculated, for naturally ventilated (NV) and for centrally air-conditioned (HVAC) buildings, the regression equations of the neutral temperature on the

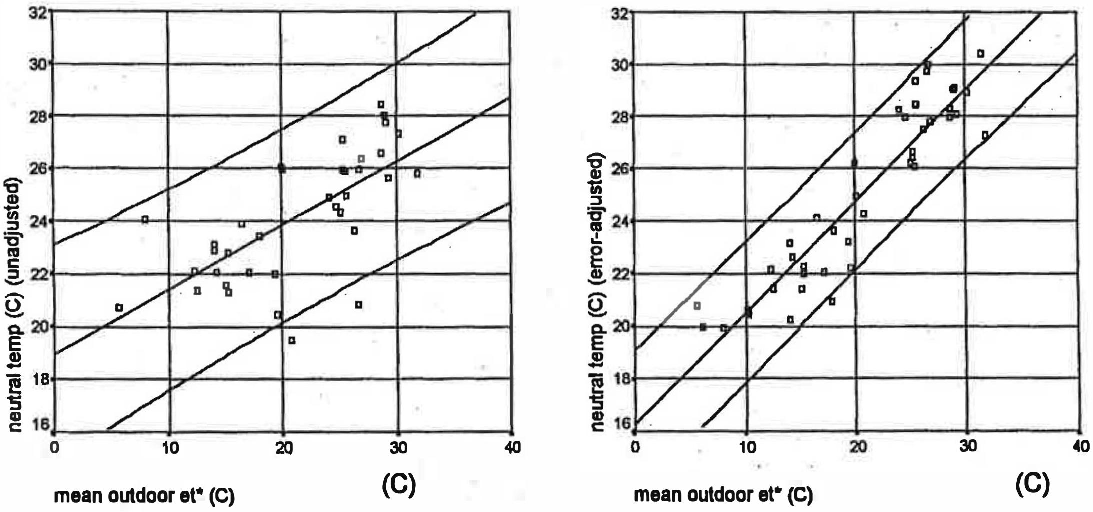

Figure 1 *Scatter diagrams for the naturally ventilated buildings showing the improvement in correlation arising from the revised neutral temperatures.*

"outdoor shade Effective Temperature (ET^*_{out})." This outdoor temperature was calculated as follows. They took the values of the air temperature and relative humidity for 6 a.m. and 3 p.m. and calculated the corresponding values of ET^*, no account being taken of wind speed or solar radiation. The mean of these two values was taken as the outdoor shade mean ET^*_{out}. Having excluded all the buildings from which the regression failed to reach significance at the 5% level, they obtained (weighted) regression equations for the neutral Operative Temperature (T_n) on this outdoor ET^*.

Naturally Ventilated Buildings

For naturally ventilated buildings, de Dear and Brager's equation was

$$T_n = 18.9 + 0.26(ET^*_{out}),\ r^2 = 0.42. \quad (2)$$

Recalculating the equation using the revised values for the neutral temperatures and weighting each according to the number of observations, we obtain

$$T_n = 15.3 + 0.47(ET^*_{out}),\ r^2 = 0.90. \quad (3)$$

The substitution of the revised neutral temperatures has sharpened the relation, enabling a much more precise estimate to be made of the probable neutral temperature at any chosen value of the outdoor temperature. It was possible to include the data from ten extra buildings. The square of the correlation is more than doubled, and the indoor neutral temperature is now seen to increase by approximately half a degree for every degree rise in the outdoor mean temperature. Figure 1 shows the two scatter diagrams.

Air-Conditioned Buildings

de Dear and Brager gave this equation, valid above −5°C outdoor mean ET^*:

$$T_n = 21.5 + 0.11(ET^*_{out}),\ r^2 = 0.53. \quad (4)$$

We have been unable to reproduce this equation precisely, perhaps because of minor corrections to the database subsequent to de Dear and Brager's analysis, leading to a different operation of the 5% significance filter. We obtain

$$T_n = 22.2 + 0.076(ET^*_{out}),\ r^2 = 0.48. \quad (5)$$

The revised neutral temperatures give the (weighted) curvilinear regression equation

$$T_n = 22.6 - 0.0039(ET^*_{out}) + 0.0024(ET^*_{out})^2,\ r^2 = 0.50. \quad (6)$$

With negligible loss of precision, this may be simplified to

$$T_n = 22.6 + 0.0022(ET^*_{out})^2,\ r^2 = 0.50. \quad (7)$$

For the HVAC buildings, the differences between the estimates of the neutral temperatures by the two methods are usually small because the mean comfort votes from the surveys in these buildings are usually close to neutrality. The chief difference between the de Dear and Brager relation and the present one arises from the buildings that were excluded by their 5% significance filter. This filter happened to exclude the data from almost all the buildings in cold climates, so their relation does not extend below an outdoor mean temperature of −5°C. The revised calculation enables the inclusion of all the buildings and reveals a curvilinear relation with the outdoor temperature. Figure 2 shows the two scatter diagrams. This is a useful extension of the range of application.

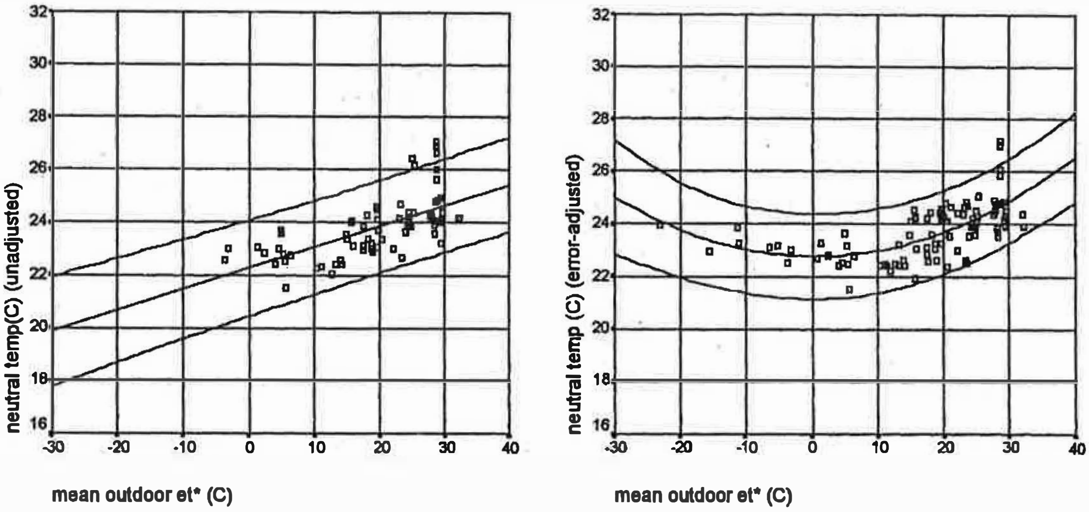

Figure 2 *Scatter diagrams for the HVAC buildings showing the extension of the useful range achieved by using the revised neutral temperatures (right).*

Omitted from the figure, and from the calculations, are Brown's data from industry. Their higher levels of activity yielded lower neutral temperatures. Their exclusion makes little difference to the weighted regressions because of the small number of observations.

COMPARISON WITH EARLIER WORK

It would be interesting to compare these relations with the original relation of this kind (Humphreys 1978), derived from an older but much larger and more diverse database, drawing together thermal comfort data from the period 1935-1975. The 1978 relations are shown in Figure 3. Comparison is not straightforward because there are certain methodological differences. The 1978 relation used the mean outdoor air temperature rather than the ET^*_{out} as the index of climate, and the classification of the buildings was subtly but importantly different. To enable comparison, de Dear and Brager's 1998 relations are (1) recalculated in terms of outdoor air temperature, and they are (2) reclassified according to the 1978 system. The 1978 relations are then (3) adjusted to allow for the use of the revised regression coefficient.

Naturally Ventilated/Free Running Buildings

1. *Recalculating the NV sample in terms of the outdoor air temperature.* The 1978 relation used the (monthly) mean outdoor air temperature (Ta_{out}) rather than the ET^*_{out}. To remove this difference, the relation from the ASHRAE database can be recalculated using the air temperature. Recalculating Equation 3 for the NV sample yields the equation

$$T_n = 15.2 + 0.48(Ta_{out}),\ r^2 = 0.90. \quad (8)$$

This equation should be compared with Equation 3. Its intercept and coefficient are virtually unchanged by the substitution, as is its correlation. So it seems that no difference in the estimate, or advantage in its precision, is attributable to using the mean shade ET^*.

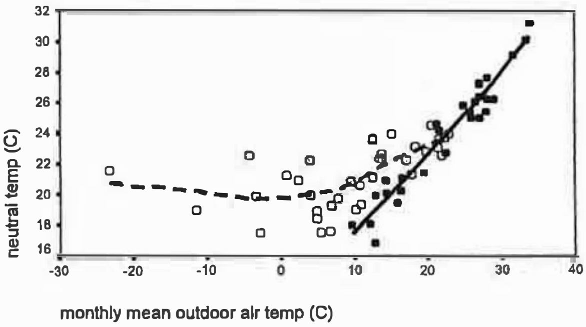

Figure 3 *The data from Humphreys (1978). The filled points are for the free-running buildings; the open points are for heated or cooled buildings. The trend lines are by Lowess smoothing (80%, three iterations).*

2. *Applying the 1978 classification to the NV sample.* The 1978 relation used a different classification for the batches of data. The nearest equivalent to de Dear and Brager's NV category is the "free running" category in the 1978 analysis. The buildings in this category were indeed naturally ventilated buildings, but that was not the criterion. "Free running" meant that at the season of the survey, neither heating nor cooling was in operation. No energy was being actively supplied to the heating or cooling plant. Thus, the same buildings in the heating season would be classified, not as "free running," but as heated or cooled.

The two classifications can be made the same in this instance by removing from de Dear and Brager's NV sample those very few naturally ventilated buildings that were surveyed during their heating season. The recalculated equation for the free running buildings in the de Dear database is

$$T_n = 13.5 + 0.546(Ta_{out}),\ r^2 = 0.91. \quad (9)$$

The equation should be compared with Equation 8. The removal of the few heated buildings has made a small but noticeable difference to the equation, reducing the intercept while increasing the regression coefficient. There is almost no change in the correlation. However, the equation would have been profoundly different had the ASHRAE database included winter surveys from naturally ventilated buildings in cold climates.

3. *Correcting the 1978 relation to allow for the use of the revised neutral temperature.* The 1978 relation for the free running buildings was

$$T_n = 11.9 + 0.534(Ta_{out}),\ r^2 = 0.94. \quad (10)$$

Regression analysis, probit analysis, or both were used to calculate the neutral temperatures. The two methods produced very similar results. It is necessary to adjust these neutral temperatures to the values that would have been obtained had an allowance been made for error in the regressor. It is not possible to correct each of the neutral temperatures individually to allow for the difference between the regression coefficient and the corrected coefficient because of the disparate subjective scales used in early thermal comfort research. It is, however, possible to make an overall correction to the regression line. Humphreys (1981) noted that for the free running buildings in the sample, the mean indoor temperature was, on average, 2.4 K above the neutral temperature and that this difference was stable across the range of outdoor temperature. Those studies that used a seven-category scale returned, on average, a regression coefficient of 0.23 scale units/K. Replacing this by the adjusted coefficient of 0.5 units/K would, on average, raise the neutral temperatures by 1.3 K. The corrected line would therefore be raised by this amount:

$$T_n = 13.2 + 0.534(Ta_{out}),\ r^2 = 0.94. \quad (11)$$

The comparison between the 1978 and 1998 relations for free running buildings may now be made with confidence that the relations could be expected to describe much the same phenomenon. The relations are:

$$(1978)\ T_n = 13.2 + 0.534(Ta_{out}),\ r^2 = 0.94 \quad (12)$$

and

$$(1998)\ T_n = 13.5 + 0.546(Ta_{out}),\ r^2 = 0.91. \quad (13)$$

Discussion. The relationships are strikingly similar in spite of a lapse of some 40 years between the dates at which the surveys were conducted. This suggests that, for free running buildings, the statistical relationship between the indoor neutral temperatures and the prevailing outdoor temperature has been remarkably stable. It follows that an adaptive comfort standard could be formulated and used with confidence. The stability presumably rests, at least in part, on an overarching effect of the climate on the temperatures achievable in such buildings and on the seasonal and cultural variations in clothing.

Comparing the HVAC/Heated or Cooled Buildings

The relation from the ASHRAE database for the HVAC buildings may be recalculated applying to the database the 1978 classification "heated or cooled." This brings into the sample those buildings that, while not being air conditioned, were surveyed during their heated season. The relationship for this new sample is recalculated using the outdoor mean air temperature. A quadratic fit appears to be reasonably satisfactory over the range of the outdoor temperature but should not be extrapolated. The relation is

$$T_n = 22.3 - 0.017(Ta_{out}) + 0.0035(Ta_{out})^2,\ r^2 = 0.49 \quad (14)$$

With little loss, a simplified equation is

$$T_n = 22.2 + 0.0030(Ta_{out})^2,\ r^2 = 0.49. \quad (15)$$

It differs slightly from Equation 7, but the differences do not reach statistical significance. The difference between ET^*_{out} and the air temperature is trivial, below 20°C, and the change makes negligible difference to the relationship.

It remains to adjust the 1978 relation for heated and cooled buildings to allow for the effect on the neutral temperatures of the adjusted regression coefficient. The same method is used. Humphreys (1981) noted that for the heated or cooled buildings in the sample the mean indoor temperature was, on average, 0.6 K above the neutral temperature. The correction to be applied would, on average, raise the neutral temperatures by 0.3 K. The corrected line would therefore be raised by this amount. Prior to correction the relation was

$$T_n = 19.8 + 0.0077(Ta_{out})^2,\ r^2 = 0.44 \quad (16)$$

So after adding the correction, it becomes

$$T_n = 20.1 + 0.0077(Ta_{out})^2,\ r^2 = 0.44. \quad (17)$$

The two equations to be compared, for heated or cooled buildings, are, therefore,

$$(1978)\ T_n = 20.1 + 0.0077(Ta_{out})^2,\ r^2 = 0.44, \quad (18)$$

and

$$(1998)\ T_n = 22.2 + 0.0030(Ta_{out})^2,\ r^2 = 0.49. \quad (19)$$

Discussion. It is notable that both equations show a curved relation of similar form with a minimum indoor comfort temperature occurring when the outdoor temperature is in the region of 0°C. In this region the older data predict lower comfort temperatures by some 2 K, a statistically significant difference. It is possible that this is attributable to a gradual rise in customary winter indoor temperatures over the

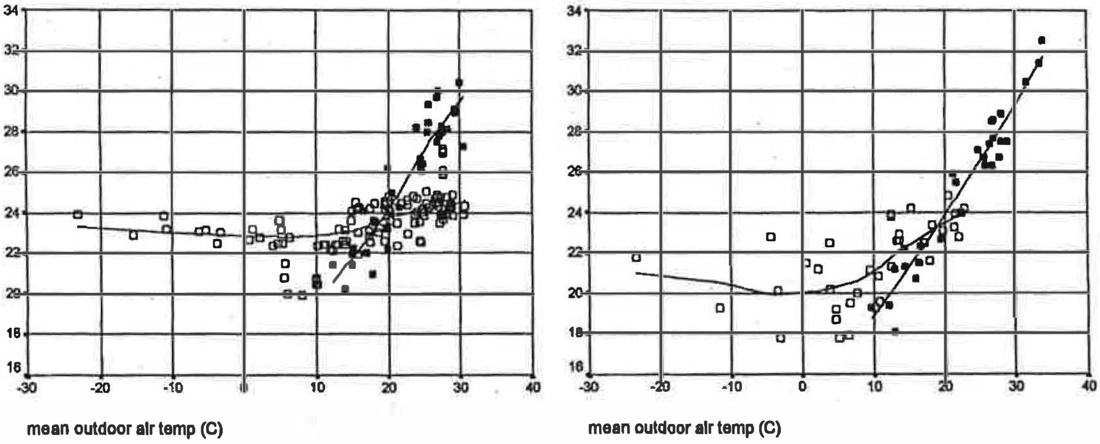

Figure 4 *Comparing the relations from the ASHRAE database (left) with the relations from the 1978 data (right), both sets including adjustment for regressor error. The filled points are from the free running buildings. The trend lines are by Lowess smoothing (80%, three iterations).*

decades, a rise to which people have become adapted. Alternatively, it may be attributable to a dominance of North American data in the ASHRAE database. In the 1978 analysis, the surveys from North America tended to yield winter comfort temperatures higher by some 2 K than did equivalent European studies. The two equations give the same result in the region of 20°C outdoor mean temperature. The same applies at –20°C, but the data from cold climates in the 1978 data are too few for there to be confidence in this comparison.

The relation with the climate is much looser for these buildings than for the free running buildings, but it does provide context for suggesting appropriate indoor temperatures, typical of current practice. They show that when the heating or cooling plant is in operation, the neutral temperature may be found to lie within a fairly wide zone, with a modest but real dependence on the climate. The basic shape of the relation has not changed over the decades.

Visual Comparison of the 1978 and 1998 Data

Figure 4 gives an overall visual comparison of the 1978 and 1998 data. The trendlines were formed by applying Lowess smoothing. They give a useful indication of the shape of the relations, both for the heated and cooled buildings and for the free running buildings. It is seen that both sets produce similar shapes of smoothed curve, practically straight for the free running buildings and curved for the heated and cooled buildings. For the latter, the curvature is more pronounced for the earlier data.

CONCLUDING COMMENTS

The paper has demonstrated the usefulness of applying a correction to the regression coefficient to allow for the effect of error in the regressor variable. The result appears to be an improved evaluation of neutral temperatures from thermal comfort field studies. It is likely that a similar improvement would result from applying a related method to the derivation of preferred temperatures from the probit analysis of the McIntyre scale values,[1] thus enhancing knowledge of the relation between thermal neutrality and thermal preference.

Applying the adjustment to the ASHRAE database of field studies improved the precision of the results, chiefly for the surveys from the naturally ventilated unheated buildings. It shows that for such buildings the recent results virtually coincide with the results from the 1978 global meta-analysis of thermal comfort field studies.

The revised approach enabled the smaller studies to contribute useful information. This made practical the use of data from more of the buildings for the estimate of the relationship for the HVAC and heated buildings. The data suggest that there may have been a rise in the winter neutral temperatures over the decades, but the effect could alternatively be attributed to differences between cultures in Europe and North America. A thorough comparison of national customs for indoor temperature and clothing would be informative. The neutral temperatures from these buildings are, at any outdoor mean temperature, more variable than those from free running buildings.

The outdoor mean shade ET^*_{out} does not improve on the outdoor mean air temperature in the role of statistical predictor for the indoor neutral temperature. In the proposed new adaptive standards, the simpler measure might be preferable, until a more complete index can be shown to be advantageous.

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1. McIntyre scale: prefer warmer (-1), no change (0), prefer cooler (1).

The strong similarity between the findings of 1978 and 1998 revealed in the comparisons of the relationships suggests that an adaptive comfort standard could be formulated for such buildings and that there could be confidence in the stability of such a standard over a period of some decades.

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