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Choice of a thermal index for architectural design with climate in Nigeria

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Abstract

Thermal indices are used to measure the degree and nature of thermal stress. Dozens of these have been developed, but the various ranges of application and accuracy in the Nigerian climate complicate choice of the most appropriate index. This study compares various thermal indices to determine which one is most reliable in the prediction of thermal stress. The thermal indices compared are the Mahoney scale, the Evans scale, the Bioclimatic chart, TSENS and the effective temperature. The study uses a mental assessment test to record thermal stress for 203 cases and then predicts the thermal stress for the same conditions using the selected thermal indices. The indices were then ordered by ranking them according to their ability to predict thermal stress using frequency analyses, ordinal- and interval-level data analyses. The little-known Evans scale was shown to be generally more accurate. The conclusion is however limited by the very nature of thermal comfort and the scope and duration of the study.
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1. Introduction

Architectural design with climate aims at keeping microclimatic conditions in dwellings within the comfort limits, irrespective of the external conditions. A thermal index measures the stress imposed by external conditions and predicts the optimal environment needed for comfort within dwellings. It offers the architect a scientific chance of evaluating comfort. Knowledge of the thermal stress is necessary for the design of walls, roofs and shading devices. The choice of the most appropriate index is however difficult. The selection is between over 30 indices that are valid

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only for certain conditions. What is needed is not only a scientific selection, but also a validation of the thermal index most appropriate for the particular climate, in this case that of Nigeria.

The most appropriate index should not only accurately measure and predict thermal stress but should also be based on easily available environmental data. It should be possible to build a computer model of the index. Assessment of the climatic compatibility of architectural design usually involves computer models (Ogunsote, 1991a).

2. Factors affecting thermal comfort

Six major factors determine comfort. They are ambient air temperature, humidity, radiation, air movement, intrinsic clothing and level of activity. Other factors that may have some effect on thermal comfort are age, sex, body shape, state of health, ethnic grouping, diet, sleep, colour of clothing, acclimatisation, availability of fresh air, transients, colour of a space enclosure and noise. The way the minor factors listed above affect comfort is not well understood. Fanger, Breum, and Jerking (1975), among others, however claims that the effects of ethnic grouping, colour of a space enclosure and noise are negligible. An indication of the relative importance of these other factors is the fact that when all the six major factors are within an acceptable and optimal range, about 70% of the population will be comfortable.

3. The thermal indices

According to Bedford (1961) and Markus and Morris (1980), work on thermal comfort started as early as 1733 AD when Arbuthnot pointed out the chilling effects of wind through dispersal of the layer of warm, moist air around the body. Knowledge of the way different variables affect thermal comfort has been used to formulate thermal indices or thermal scales that indicate the effects of combining the different variables on comfort. Over 30 of these indices have been devised and they state generally the thermal stress given the following six variables: ambient air temperature, mean radiant temperature, air velocity, humidity (relative humidity or vapour pressure), intrinsic clothing and level of activity.

An ideal index should reasonably accurately predict the consequences of any combination of the six major factors affecting comfort. It should be applicable both indoors and outdoors and it should be capable of indicating the degree of discomfort. The following are some of the most common thermal indices.

3.1. *Bioclimatic chart*

This chart was developed by Victor Olgyay and it shows the combinations of air temperature and relative humidity that are comfortable (Olgyay, 1963). The original version has undergone several modifications and it now indicates how the comfort zone is shifted by air movement, radiation, and to a limited extent—clothing and activity.

3.2. BRS method

This was developed at the Building Research Station (Humphreys, 1971). It expresses the comfort zone based on globe or air temperature and this varies with activity, clothing and air movement (Humphreys, 1976a, b).

3.3. Corrected effective temperature (CET)

This is an improvement on the effective temperature (ET) and it incorporates the effect of radiation. This is achieved by using the globe temperature instead of the dry bulb temperature.

3.4. DISC

This gives a direct comparison between any combination of conditions in terms of the degree of cold or warm discomfort experienced, at any combination of the six major variables affecting thermal comfort. The value of DISC ranges from -5 to $+5$, with a central neutral point labelled zero.

3.5. Effective temperature (ET)

This is the temperature of a still, saturated atmosphere that would, in the absence of radiation, produce the same effect as the atmosphere in question. The scale incorporates the effects of relative humidity, air velocity, air temperature and clothing.

3.6. Evans scale

This is a dry-bulb temperature scale proposed by Martin Evans and it incorporates the effects of relative humidity, air movement, metabolic rate and clothing. These variables are grouped to reduce the number of possible combinations. It is very similar to the Mahoney scale (Evans, 1980).

3.7. Heat stress index (HSI)

Belding and Hatch (1955) developed this index at the University of Pittsburgh. It is based on several physiological assumptions and it uses theoretical calculations of the external heat stress, the heat produced by metabolism and the evaporative capacity of the environment. It considers all the six variables except clothing.

3.8. Index of thermal stress (ITS)

Givoni (1963) established this index from first principles. It computes the total thermal stress using a biophysical model describing the mechanisms of heat exchange between the body and the environment, assuming thermal equilibrium. The index has a negative value for cold discomfort and a positive one for warm discomfort.

3.9. Mahoney scale

Carl Mahoney (working with Koenigsberger and Evans) proposed this scale for the determination of thermal stress in climate analysis (Koenigsberger, Ingersoll, Mayhew, & Szokolay, 1974, p. 241). It uses four variables to determine comfort: the annual mean temperature, the humidity group, the period (whether day or night), and the air temperature (Mahoney, 1967).

3.10. Operative temperature

This is the uniform temperature of an imaginary enclosure in which man will exchange the same dry heat by radiation and convection as in the actual environment. It is in effect a measurement of the dry heat loss from the body. The operative temperature thus depends on the mean radiant temperature, the air temperature and the air velocity since this increases convection. The value of the operative temperature approaches that of the air temperature with increase in air velocity.

3.11. Predicted four hours sweat rate (P4SR)

This was developed by McAriel et al. (1947) in England and is based on the sweat rate resulting from a 4 h exposure to given conditions. The index is in the form of a nomogram and it accounts for various categories of clothing, air velocity and metabolic rate.

3.12. Resultant temperature

Missenard (1948) developed this index in France. It is very similar to the ET but the duration of exposure is greater than that used for the ET. It is valid for rest conditions and there are two nomograms: one for clothed and another for unclothed subjects.

3.13. Standard effective temperature (SET)

The standard effective temperature is an improvement on the ET and it expresses any environment in terms of an environment standardised at 50% relative humidity, still indoor air conditions, sedentary metabolic rate and normal lightweight indoor clothing (Gagge, Nishi, & Gonzalez, 1973).

3.14. TSENS

This is a thermal sensation scale proposed by Rholes and Nevins (1971). It is a 10-point scale ranging from −4 to +5 with a central neutral point labelled zero. Markus and Morris (1980, p. 57) provide an equation that determines TSENS given the ambient or operative temperature and the vapour pressure at dew-point temperature. This equation is valid for the standard conditions on which SET is based.

3.15. Other indices

The equivalent warmth (EW) was proposed by Bedford (1961) in England. It is thought to be unreliable at high temperatures and to underestimate the cooling effect of air movement at high humidities. The equatorial comfort index (ECI) was developed by Webb (1960) in Singapore and it is similar to the ET. The wind chill index was developed to determine the degree of discomfort rather than to define comfortable conditions.

4. Advantages and limitations of the thermal indices

The various thermal indices have advantages and limitations that affect their applicability to the determination of thermal comfort in the climatic design zones of Nigeria (Table 1). The

Table 1
Advantages and limitations of selected thermal indices

Index	Advantages	Limitations
Bioclimatic chart	It is a simple graphical method that is very popular	Cannot predict the degree of discomfort and has limited use for relative humidities below 15% and above 75%
BRS method	Institutional support	It is not reliable above 26°C since it does not allow for variation in cooling caused by sweating at different humidities above this temperature
Effective temperature (ET)	It shows the effect on comfort of all the major factors except radiation and activity. The nomogram is simple and easy to use	Analyses indicate that it overestimates the effects of humidity under cool and comfortable conditions and underestimates the effect of humidity at high temperatures
Evans scale	This is a simple scale derivable from readily available data. It distinguishes between day and night comfort limits and it may be used both indoors and outdoors	It does not express the degree of discomfort. It generalises by classifying relative humidity into 4 categories and annual mean temperature into 3 categories
Heat stress index (HSI)	It analyses the relative contribution of the various factors affecting thermal stress	Koenigsberger claims that it is reliable only between 27°C and 35°C and 30% and 80% relative humidity
Index of thermal stress (ITS)	It has a solid academic and experimental backing that has hitherto not been challenged	Valid only for stable, even if elevated body temperature and pulse rate
Predicted four hours sweat rate (P4SR)	Various studies have confirmed the validity of the index at high temperatures	It is thought to be unsuitable for temperatures below 28°C and to underestimate the cooling effect of air movement at high humidities
Resultant temperature	Givoni claims that it is more accurate than the ET	It is thought to underestimate the cooling effects of air movement over 35°C and 80% RH
TSENS	It expresses the environmental conditions in terms of comfort or discomfort felt	The formula available determines TSENS only for a standard set of conditions

advantages and limitations of the CET index and the Mahoney scale are similar to those of the ET index and the Evans scale, respectively.

4.1. Range of applicability

The thermal indices are usually applicable only in certain conditions, usually defined by environmental ranges. This range of applicability is however only specified for some indices. Furthermore, analyses of these indices by others often conclude that they are applicable in a much narrower range of conditions than claimed.

5. Research methodology

The object of this study is to compare the various thermal indices to determine which one is most reliable in the prediction of thermal stress. It is possible to record the thermal stress experienced for various conditions and to predict the thermal stress for the same conditions using the thermal indices. The recorded and predicted thermal stresses can then be compared. The best index will be consistently more successful at predicting the thermal stress in a wide range of environmental conditions.

5.1. Choice of methodology for comfort study

There are three tests used in psychophysical experiments—performance tests, physiological tests and mental assessment tests. The choice of an appropriate method was determined by limitations. The equipment needed to create artificial environments and to measure performance and biological variables were not available. A mental assessment test using rating scales was therefore designed. This had the advantage of providing mental assessments of the actual climatic conditions and not an artificially simulated environment. On the other hand, various subjects rate comfort under varying conditions and comparison is thereby made more difficult. This comparison was made possible by recording background information about which the subject was not necessarily aware and using mathematical methods to harmonise the varying conditions.

6. Selection of thermal indices for comparison

Ideally, the applicability of all the aforementioned indices should be determined. However, technical constraints make this impractical. The major impediment was the non-availability of sufficient information concerning some of the indices. Secondly, some of them are not easily amenable to computerisation while manual determination of thermal stress is tedious and error prone. The following indices were finally selected.

6.1. The Mahoney scale

The air temperature was used to determine the thermal stress depending on the annual mean temperature and the humidity group.

6.2. The Evans scale

The thermal stress using this index was determined using the same procedure as in the case of the Mahoney scale.

6.3. The Bioclimatic chart

This determines the thermal stress using the air temperature, the relative humidity, the air velocity and the solar radiation. The air velocity was determined from wind information and the solar radiation estimated from cloud cover.[1]

6.4. TSENS

This used the air temperature on the condition that the relative humidity was between 30% and 70%, that the clothing was light or normal, and that there was no wind (calm). All cases not satisfying these conditions were rejected.[2]

6.5. The effective temperature

The ET was determined from the air temperature, the relative humidity and the air velocity. All cases where the subject was not shaded from direct solar radiation or where the subject was clothed heavily were rejected.[3] Two comfort limits were used to obtain two different but related scales. The comfort limits are 22–27° and 20–25°.[4]

7. The field study

A form (questionnaire) was designed to record thermal stress on a 9-point scale along with other information of interest such as location, date, time, age, sex, height, weight and dressing of subject, and climatic conditions, wind, cloud cover, rainfall and shading. Subjects were asked five questions including their state of thermal comfort. The researcher then recorded the answers along with other observations on the study form. The form was used to document 203 cases on the Main Campus of Ahmadu Bello University, Zaria between August and October 1987. The frequency distribution of the thermal stress recorded is shown in Table 2.

[1] The IHVE Guide and the Beaufort scale were used to approximate air velocity for the four categories of observed wind speed. The solar radiation was approximated from tables for Zaria based on cloud cover.

[2] Only 71 cases were left for analysis after this elimination.

[3] This leaves 181 cases for analysis.

[4] A related study attempted to establish comfort limits for the ET in Nigeria using the same data from the field study.

Table 2
Frequency distribution of thermal stress on a nine-point scale

Thermal stress	Number of cases
Very cold	5
Cold	14
Cool	38
Comfortably cool	66
Comfortable neutral	39
Slightly warm	14
Warm	11
Hot	10
Very hot	6
Total	203

Table 3
Frequency distribution of thermal stress on a five-point scale

Re-coded thermal stress	Number of cases
Very cold	5
Cold	52
Comfort	119
Hot	21
Very hot	6
Total	203

For uniformity, the recorded thermal stress was re-coded.[5] Comfortably cool, comfortable neutral and slightly warm were re-coded as "comfort". Cold and cool were re-coded as cold, while warm and hot were re-coded as hot. The frequency distribution obtained is shown in Table 3.

7.1. *Determination of predicted thermal stress*

The study made use of a data library in computer-readable form.[6] The date was used to obtain the minimum and maximum air temperature and relative humidity for the 15-day period (long-term averages). The annual mean temperature was obtained at the same time. The time of the day was used to calculate the air temperature for the nearest quarter hour.[7] This was done with the aid of the hourly temperature calculator. The average relative humidity was also found. The thermal stress was found for the Mahoney and Evans scales using the necessary variables. The discomfort

[5] This re-coding created fewer groups and made analysis easier. The use of a 5-point scale instead of a 9-point scale also reduced the chances of an error of prediction. For thermal sensation scales see Markus and Morris (1980, pp. 52–57). See also Rholes and Nevins (1971).

[6] The data library contains climatic and related data. See Ogunsote and Prucnal-Ogunsote (1987a, b).

[7] This rationalisation was introduced to enable compatibility with existing software. Furthermore, the temperature variation over a period of seven and a half minutes is usually small and often below 0.1°C.

scale proposed by Prucnal-Ogunsote and Ogunsote (1988) was used for these and other indices except TSENS. The vapour pressure at dew-point temperature was determined from a table and this was used with the air temperature to determine TSENS. The thermal stress thus obtained was then converted using a 5-point scale.

For the ET the minimum and maximum wet bulb temperatures were calculated using the psychometric chart. The minimum and maximum ETs were then determined for the air velocity obtained from the wind information.[8] The ET for the given time was found with the aid of the hourly temperature calculator and the thermal stress finally determined by comparing the calculated ET with the appropriate comfort limits.

8. Comparison of the indices

The determination of the predicted thermal stress for over 200 specific situations using several thermal indices is a huge mathematical task. This was made even more difficult by the need to determine the values of the climatic variables at specified times using complex algorithms. The thermal stress thus obtained was analysed using various statistical techniques requiring the use of modern mathematical concepts. In the midst of this numerical deluge, it is easy to lose sight of the main objective of the study, to fail to detect mathematical blunders or to misinterpret data (Ogunsote, 1990, 1991b).

The need for qualitative analyses in this type of situation cannot be over-stressed. It is necessary to examine all data and results for logic in relation to existing knowledge. The results obtained were compared with existing knowledge, and when anomalies were observed, they were investigated and noted. Such anomalies were never discarded unless they could be directly traced to some systematic disturbance of or fluctuation in the controlled conditions.[9]

To facilitate easy computation and reliability and to make checking possible the computations were handled by a computer. Several routines were written in FORTRAN and these coupled with the existing suite of programs were used to determine the thermal stress (Ogunsote, 1986). The statistical analyses were done with the aid of SPSS—statistical package for the social sciences.[10]

9. Ordering of the indices

Ordering of the indices involved ranking according to their ability to predict thermal stress. The type of statistical technique used depends on the nature of the data and the level of measurement (Harshberger, 1977). The scales of measurement are nominal, ordinal, interval and ratio.

The five categories of thermal stress on a 5-point scale give an ordinal scale, since there are distinguishable groups with an order of magnitude among the groups, or an interval scale on the

[8] The predicted thermal stress for the study using the ET scale was obtained with the aid of the air velocity. The four categories calm, slight breeze, strong breeze and strong wind were graded as 0.5, 2.5, 4.5 and 7.0 m/s, respectively. The speed at body level is obtained by applying a reduction factor of 0.3.

[9] Meyer (1975, pp. 17–18) discusses rejection of data including Chauvenet's criterion and its dangers.

[10] SPSS version 6.50 and the MNF compiler were used on the CDC Cyber 72 under the NOS version 1.1 Operating System at the Iya Abubakar Computer Centre, Ahmadu Bello University, Zaria in 1987.

assumption that the units are the same size throughout. It is difficult to decide whether the differences between cold and comfortable on one hand, and hot and very hot on the other are the same. In making a decision, it should be noted that the level of measurement increases from nominal to ordinal to interval and to ratio. Interval-level data therefore have all the properties of ordinal-level data. It is also necessary to establish whether the data are continuous or discrete. Thermal stress can be measured on a continuous scale, but for the purposes of this study grouping into five categories has been used to obtain discrete data.

The statistical techniques used in the analysis of the data are frequency analysis, ordinal-level data analysis and interval-level data analysis (Nie, Hull, Jenkins, Steinbrenner, & Bent, 1975).

10. Frequency analysis

Frequency analysis may give an indication of the relationship between the predicted and observed thermal stress. One such analysis is the analysis of the frequency distribution of error of prediction in percentages (Table 4). The expression of the distribution in percentages enables easy comparison, especially when different numbers of cases are involved. The statistics for an ideal thermal index should exhibit the characteristics shown in Table 5. The statistics of error of prediction for the various indices are shown in Table 6. Frequency curves may also be constructed

Table 4
Frequency distribution of error of prediction for the various indices

Thermal index	Frequency distribution of error of prediction (%)						
	−3	−2	−1	0	+1	+2	+3
Bioclimatic chart	—	2.5	7.9	55.2	29.1	5.3	—
ET 22–27	0.5	6.1	21.0	51.4	18.2	2.8	—
ET 20–25	—	1.7	10.5	49.7	30.4	7.7	—
Mahoney scale	—	1.0	9.9	38.9	36.9	12.3	1.0
TSENS	—	—	2.8	38.0	42.3	15.5	1.4
Evans scale	1.0	9.4	19.7	37.4	25.6	6.9	—

Table 5
Expected characteristics of statistics of error of prediction

Statistic	Value
Frequency of zero error of prediction	Very large
Mean	Zero or very small
Median	Zero or very small
Mode	Zero
Range	Small
Skewness	Zero or very small
Standard deviation	Small
Sum	Zero or very small

Table 6
Statistics of error of prediction for the various indices

Thermal index	Mean	Median	Sum	Standard deviation	Mode	Skewness
Evans scale	−0.02	0.03	−4	1.09	0	−0.256
ET 22–27	−0.11	−0.07	−20	0.89	0	−0.261
Bioclimatic chart	0.27	0.22	55	0.78	0	−0.143
ET 20–25	0.32	0.26	58	0.83	0	−0.006
Mahoney scale	0.53	0.51	107	0.93	0	0.020
TSENS	0.75	0.72	53	0.81	1	0.322

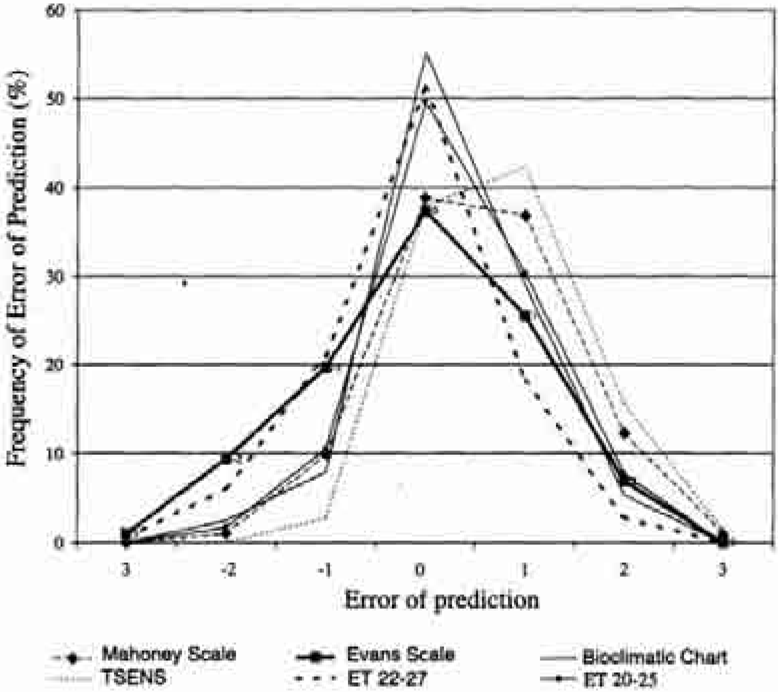

Fig. 1. Frequency curves of error of prediction.

for the various indices and then compared (Fig. 1). A good index should show a symmetrical distribution about the error of prediction axis, a high frequency of zero error of prediction and a low range of error of prediction.

10.1. Analysis of the cumulative frequency of error of prediction

An analysis of the cumulative frequency of error of prediction was also made. This showed the cumulative percentage of successful predictions given error levels of 0, ±1, ±2 and ±3. An ideal index should make a 100% successful prediction at the zero error level. The higher the error level before a certain percentage of successful prediction is achieved, the less appropriate the index

Table 7
Cumulative frequency distribution of error of prediction for the various indices

Thermal index	Error of prediction			
	0	±1	±2	±3
Bioclimatic chart	55.2	92.2	100.0	—
ET 22–27	51.4	90.6	99.5	100.0
ET 20–25	49.7	90.6	100.0	—
Mahoney scale	38.9	85.9	99.0	100.0
TSENS	38.0	83.1	98.6	100.0
Evans scale	37.4	82.7	99.0	100.0

Table 8
Percentage of successful predictions for under-heating, comfort and overheating

Thermal index	Success ratings			
	Under-heating	Comfort	Overheating	Average
Mahoney scale	10.5	47.9	81.5	46.6
ET 20–25	11.3	68.8	56.3	45.5
Evans scale	28.1	47.9	59.3	45.1
TSENS	0	42.9	81.8	41.6
Bioclimatic chart	0	89.1	25.9	38.3
ET 22–27	28.3	73.2	0	33.8

(Table 7). This type of analysis however has a few drawbacks inherent in the distribution of observed thermal stress. In the study, 58.6% of subjects expressed comfort, and an index that is incapable of detecting hot or cold discomfort and always predicts comfort will seem to be a good index. Thus, the Bioclimatic chart, which predicts comfort for a wide range of conditions, was favoured by this method of analysis.

10.2. Ability to predict under-heating, comfort and overheating

An alternative approach is to determine the ability of the index to predict under-heating, comfort and overheating. For this purpose hot discomfort and very hot discomfort were grouped as overheating while cold discomfort and very cold discomfort were grouped as under-heating. The percentages of successful predictions for under-heating, comfort and overheating are given in Table 8. This table shows that all the indices exhibit a bias in their ability to predict thermal stress. Some are good at predicting under-heating while others are capable of detecting overheating.

11. Ordinal-level data analysis

This treats both the observed and the predicted thermal stress as ordinal-level data. In this case the difference between cold and comfortable need not be the same as that between comfortable

Table 9
γ, Kendall's τb and Spearman's ρ

Index	γ	τb	Sign (τb)	ρ	Sign (ρ)	No. of cases
Evans scale	0.28	0.177	0.001	0.203	0.004	203
Mahoney scale	0.27	0.155	0.002	0.169	0.017	203
Bioclimatic chart	0.27	0.103	0.030	0.108	0.124	203
ET 20–25	0.25	0.134	0.008	0.146	0.051	181
ET 22–27	0.11	0.052	0.297	0.056	0.457	181
TSENS	0.10	0.051	0.530	0.054	0.658	71

and hot. Correlation between ordinal-level data is analysed using the γ test, Kendall correlation coefficient (τ) and Spearman correlation coefficient (ρ).

11.1. γ test of statistical significance

γ is the probability of correctly guessing the order of a pair of cases on one variable once the other variable is known. The sign indicates the direction of ordering.

11.2. Kendall's rank-order correlation coefficient (τ)

Kendall's τ is a standardised coefficient based on the amount of agreement between two sets of ordinal rankings. Kendall's τ is very similar to Spearman's ρ but the Kendall's coefficient is more meaningful when the data contain a large number of tied ranks. Kendall's τ is non-parametric because it does not depend upon a normal distribution or the metric quality of interval scales.

11.3. Spearman's rank-order correlation coefficient (ρ)

Spearman's ρ is defined as the sum of the squared differences in the paired ranks for two variables over all cases, divided by a quantity which is what the sum of the squared differences would have been had the two sets of rankings been totally independent.

These coefficients are shown in Table 9. The Martin Evans thermal scale consistently exhibited the highest correlation. The ET 20–25 scale showed the higher correlation among the variations of the ET index.

12. Interval-level data analysis

This treats both the observed and the predicted thermal stress as interval-level data. In effect, the comfort conditions very cold, cold, comfortable, hot and very hot are assumed to occur at equal intervals on the comfort scale. Interval-level data are examined for correlation using two statistics: Pearson correlation coefficient (r) and η correlation ratio (η^2).

Table 10
Pearson correlation coefficients and η correlation ratios

Index	Pearson corr. coefficient	Significance	η correlation ratio		Number of cases
			OTS dep.	PTS dep.	
Evans scale	0.190	0.003	0.28	0.26	203
Mahoney scale	0.174	0.007	0.21	0.23	203
ET 20–25	0.154	0.019	0.21	0.22	181
Bioclimatic chart	0.113	0.054	0.11	0.17	203
TSENS	0.047	0.348	0.05	0.20	71
ET 22–27	0.045	0.275	0.05	0.13	181

OTS = Observed thermal stress dependent. PTS = predicted thermal stress dependent.

12.1. The Pearson correlation coefficient (r)

The Pearson correlation coefficient is used to measure the strength of relationship between two interval-level variables. The strength of relationship indicates the goodness of fit of a linear regression line to the data. It also indicates, when r is squared, the proportion of variance in one variable explained by the other.

12.2. η correlation ratio (η test of statistical significance)

η correlation ratio is the common name for η^2 and it has an intuitive interpretation as the proportion of variance in the dependent variable accounted for by the independent variable.[11] η is a measure of the association between two variables used when the independent variable is nominal level and the dependent variable is interval or ratio level. It shows how the means of the dependent variable are within the categories of the independent variable.

The Pearson correlation coefficients and the η correlation ratios for the various indices are shown in Table 10. The Martin Evans scale showed the highest correlation while the comfort limits 20–25 produced the best results for the ET scale.

13. Choice of a thermal index

Table 11 shows a summary of the various techniques used to order the indices according to their ability to correctly predict thermal stress.

While the various techniques produced different orders, the little known Evans scale was shown to be generally more accurate.[12] This scale however indicates only the type but not the degree of discomfort. The ET index by its very nature indicates the degree of discomfort. The index is very popular and though this study has shown that it is less accurate than the Evans scale, it has the advantage of combining the effects of additional variables. The comfort limits 20–25° have been

[11] The η correlation ratio is discussed in detail by Mueller, Schuessler, and Costner (1970, pp. 325–333).

[12] Only the day comfort limits were analysed since the study covered only the day.

Table 11
Summary of techniques used to order the indices

Method	Thermal index		
	Best	2nd Best	3rd Best
Distribution of error of prediction	Bio chart	ET 22–27	ET 20–25
Mean of error of prediction	Evans	ET 22–27	Bio chart
Skewness of error of prediction	ET 20–25	Mahoney	Bio chart
Cumulative frequency of error of prediction	Bio chart	ET 22–27	ET 20–25
Ability to predict overheating, comfort and under-heating	Mahoney	ET 20–25	Evans
χ test of statistical significance	Evans	Mahoney	Bio chart
Kendall's rank-order correlation coefficient (τ)	Evans	Mahoney	ET 20–25
Spearman's rank-order correlation coefficient (ρ)	Evans	Mahoney	ET 20–25
Pearson correlation Coefficient (r)	Evans	Mahoney	ET 20–25
η correlation ratio (PTS dependent)	Evans	Mahoney	ET 20–25
Summary	Evans	Mahoney	ET 20–25

shown to be more accurate for the ET index in Nigeria than the 22–27° generally recommended for tropical regions.

14. Practical applicability and limitations

The predicted thermal stress may differ from the thermal stress actually experienced for several reasons. The applicability of the calculated thermal stress is therefore subject to certain assumptions. Some of these limitations result from the very nature of thermal comfort while others depend on the field study. The predicted thermal stress is subject to the following limitations:

1. Comfort is subjective and the thermal stress experienced varies within the population for the same environmental conditions. The predicted thermal stress is applicable to the majority and not the whole of the population.
2. It is not clear how some factors affect thermal comfort.
3. The climatic conditions were predicted based on average long-term climatic data. The climatic conditions experienced by subjects may therefore differ from those calculated.
4. The field study covered only 3 months of the year.
5. The study covered only day thermal stress. The thermal stress predicted for the night-time may therefore require adjustment.
6. The field study was carried out only in Zaria. The application of the observations made in this study to predict thermal stress for the whole of the country may therefore produce inaccuracies.
7. The thermal stress is applicable for external conditions, light or normal clothing, healthy subjects, calm or light breeze, shade, sedentary activity and open spaces with low or medium building density.[13]

[13] Some few subjects not satisfying some of these conditions were however included in the statistical analysis.

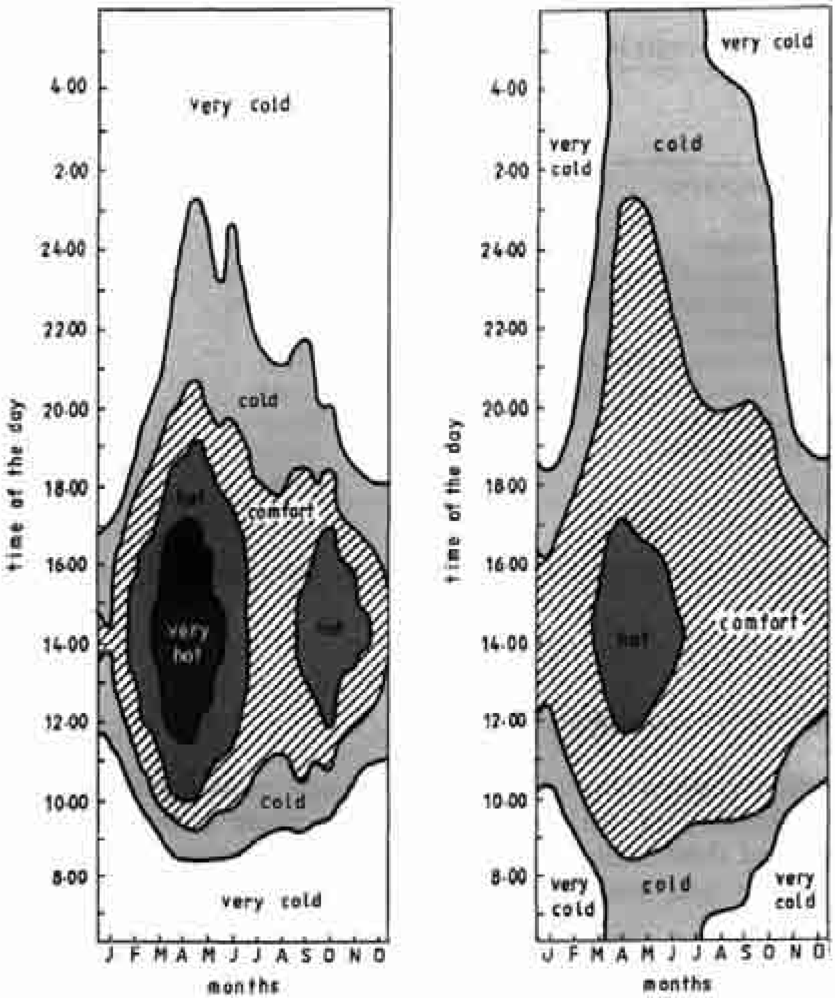

Fig. 2. The predicted thermal stress for Zaria using the Evans scale on the left (a) and the predicted thermal stress for Zaria using the ET scale with comfort limits of 20–25° on the right (b). A comparison shows significant differences but a common underlying pattern.

15. Plots of the thermal stress

Plots of the thermal stress were produced using the computer program COLDHOT and the Evans scale (Fig. 2a). COLDHOT was also used to analyse the degree of thermal stress on a monthly and biweekly basis and to calculate the percentage of the comfortable, overheated and under-heated periods (Prucnal-Ogunsote & Ogunsote, 1988). These data for Zaria are shown in Table 12. The average degree of thermal stress for selected towns in Nigeria using the Evans scale on an annual basis is also presented in Table 13.

Table 12
Degree of thermal stress for Zaria using the Evans scale

Month	Degree of thermal stress (%)		
	Comfortable	Overheated	Under-heated
January	2.1	0	97.1
February	14.6	10.4	75.0
March	12.5	25.0	62.5
April	7.3	37.5	55.2
May	9.4	34.4	56.2
June	14.6	27.1	58.3
July	30.2	1.0	68.8
August	27.1	0	72.9
September	24.0	9.4	66.6
October	10.4	21.9	67.7
November	11.5	10.4	78.1
December	15.6	0	84.4

Table 13
Average degree of thermal stress for selected towns in Nigeria using the Evans scale

Design zone	Town	Average degree of thermal stress (%)		
		Comfortable	Overheated	Under-heated
Coastal zone	Ikeja	24.8	19.0	56.2
Forest zone	Ibadan	20.9	19.6	59.5
Transitional zone I	Makurdi	16.7	28.5	54.8
Transitional zone II	Enugu	18.8	25.2	56.0
Savannah zone I	Sokoto	14.2	26.7	59.1
Savannah zone II	Zaria	14.9	14.8	70.3
Highland zone	Jos	5.9	0.6	93.5
Semi-desert zone I	Nguru	12.5	25.6	61.9
Semi-desert zone II	Katsina	12.3	20.1	67.6

Table 14
Average degree of thermal stress for selected towns in Nigeria using the effective temperature index with comfort limits 20–25

Design zone	Town	Average degree of thermal stress (%)		
		Comfortable	Overheated	Under-heated
Coastal zone	Ikeja	67.0	25.7	7.3
Forest zone	Ibadan	59.2	15.5	25.3
Transitional zone I	Makurdi	55.0	22.6	22.4
Transitional zone II	Enugu	58.1	17.1	24.8
Savannah zone I	Sokoto	42.2	14.1	43.7
Savannah zone II	Zaria	37.1	4.9	58.0
Highland zone	Jos	16.9	0	83.1
Semi-desert zone I	Nguru	41.2	15.5	43.3
Semi-desert zone II	Katsina	36.4	9.2	54.4

The plots of the thermal stress for the selected stations using the ET index and the new comfort limits were also produced using COLDHOT (Fig. 2b). The degree of thermal stress for the various stations is given in Table 14.

A comparison of the predicted thermal stress based on the plots of the thermal stress (Fig. 2) graphically illustrates the significant variations in predicted thermal stress when different indices were used. The values used for the lower and upper comfort limits are very significant. The method used to differentiate between cold discomfort and very cold discomfort on one hand and hot discomfort and very hot discomfort on the other hand is also very significant. Predictions of cold discomfort, comfort and hot discomfort using the Evans scale approximated to the prediction of comfort when the ET index (20–25°) was used.

16. Conclusion

This study has identified the Evans scale as the most successful in the prediction of thermal stress. New comfort limits (20–25°) have also been recommended for the ET index. The nature and degree of thermal stress established using these indices provide information necessary for the design of walls, roofs and shading devices. The thermal stress experienced in any of the climatic design zones is a function of the thermal stress experienced in the various towns and cities within the zone. These stations may exhibit slight variations in the pattern or degree of thermal stress. In addition, the thermal stress experienced within any particular station varies within the population and over the years. The best prediction of thermal stress for any of the climatic design zones can therefore only be a compromise and a partial reflection of the actual conditions. While this study has answered a few questions, it has asked many more. For example, the many methods used for the determination of thermal stress were scrutinised and doubts began to arise as to relevance and applicability in the Nigerian environment.

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