EVALUATING THE PERFORMANCE OF SELECTED THERMO-PHYSIOLOGICAL INDICES ON QUANTIFYING BIOCLIMATIC CONDITIONS FOR PEDESTRIANS IN A STREET CANYON

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ABSTRACT

A large number of indices have been developed to assess human bioclimatic conditions. The indices that could be considered valid in all climate and seasons are those that are based on calculations involving the heat balance equation. The aim of the present study is to evaluate the performance of selected existing indices based on body's energy balance, in an outdoor built environment. A field questionnaire survey was carried out simultaneously with microclimatic measurements in a street canyon located in the centre of Athens, Greece. The experiments that lasted 2 days, were performed in July while the interviews were conducted in randomly selected people passing by or visiting the measurements sites. The values produced by COMFA, PET and UTCI were compared to the actual thermal sensation that was indicated on a 7-point thermal sensation scale by the respondents. The results showed a significant relationship between predicted and actual thermal sensation. However indices' estimates deviated from the actual thermal sensation. The maximum percentage of correct predictions was about 37% while UTCI predicted thermal sensation better than COMFA or PET.

KEYWORDS

Thermal sensation, outdoors, predictive models, questionnaire survey

1 INTRODUCTION

Urbanization and designers' interest on internal thermal comfort, with respect to low energy consumption, led to a great number of studies on indoor thermal sensation. The models developed to estimate thermal sensation indoors were used also, without any modification, to outdoor environments. However, studies on outdoor thermal sensation demonstrated that thermal sensation differed from that predicted by the indoor models, due to unrealistic approaches such as lack of solar radiation and still air conditions (Höppe, 2002).

More recently the environmental quality of outdoor urban spaces has drawn a lot of attention for reducing heat island effect (Santamouris, 2013; 2012; Santamouris et al, 2011) and managing the potential of sun and wind due to the mutual obstructions between buildings as well as improving microclimate outdoors that influence both the bioclimatological conditions indoors and the function of the space; thus several models have been developed in the context of outdoor thermal sensation. Among the proposed ones, the state of the art in the assessment of thermal environment are the thermo-physiological indices that are based on heat balance equations. Often the predictions among the models differ (Blazejczyk et al, 2012; Jones, 2002) or the predictions of an index differ depending on the climate while there is a discrepancy between the predicted and the actual (Monteiro and Alucci, 2006; Lin and Matzarakis, 2008; Cheng et al, 2012; Pantavou et al, 2013). Lin and Matzarakis (2008) and Cohen et al (2013) calibrated Physiological Equivalent Temperature (PET) index, in order to improve its predictability while they identified differences in PET boundaries in Western/Middle Europe, Tel Aviv and Taiwan assessment scale.

Nevertheless bioclimatic models remain important tools for assessing human thermal sensation and are widely used (Pantavou et al, 2011; Theoharatos et al, 2010; Lin and Matzarakis, 2008; Gaitani et al, 2007) so it is essential to be aware of their applicability as well as to identify the model that predicts the most accurate thermal sensation in the climatic zone of interest. The aim of the present study is to evaluate the adequacy of three different models on quantifying thermal sensation in Mediterranean climates. All three theoretical models examined, Comfort Formula (COMFA), Physiological Equivalent Temperature (PET) and Universal Thermal Climate Index (UTCI), are based on human energy balance and are designed for the prediction of thermal sensation outdoors.

COMFA (Brown and Gillespie 1986, 1995) is based on estimating the energy budget of a person. PET (Höppe, 1999) is based on a two node model, the Munich Energy-balance Model for Individuals (MEMI). It is defined as the air temperature at which, in a typical indoor setting (with a water vapour pressure of 12 hPa and light air (0.1 m s^{-1}), the heat budget of the body (80 W activity, in addition to the basic metabolism: thermal resistance of clothing of 0.9 clo) is balanced with the same core and skin temperature that occurs when under the outdoor conditions to be assessed. Universal Thermal Climate Index (UTCI) (COST Action 730) is based on a multi-node model of human thermoregulation and it is independent of person's characteristics (e.g. age, gender). It is expressed as an equivalent ambient temperature (°C) of a reference environment providing the same physiological response of a reference person, as in the actual environment

2 MATERIALS AND METHODS

Field questionnaire surveys were performed simultaneously with microclimatic measurements for two days in July, one day during morning-midday and one during afternoon–evening, at the pedestrianized part of Ermou Street which is the busiest shopping street in central Athens, Greece. A mobile meteorological station equipped with a Rotronic S3CO3 thermo-hygrometer, a Second Wind C3 anemometer, two Kipp & Zonen CM3 pyranometers, an ECO pyrgeometer and a grey globe thermometer (PVC sphere, 40 mm diameter with an emissivity of 0.3) were monitoring air temperature (T_{air}), relative humidity (RH), average wind speed (WS), down-welling ($SR_{\downarrow}$) and reflected ($SR_{\uparrow}$) solar radiation down-welling and ground total radiation ($TR_{\downarrow}$, $TR_{\uparrow}$) on a horizontal plane as well as globe temperature (T_{globe}) at the height of 1.1m above the ground. The data were stored on a CR10X Campbell Scientific data logger at 1 min intervals.

The interviews were based on a structured questionnaire and were conducted in people passing by or visiting the site. The questionnaire included questions related to personal characteristics of the interviewees such as clothing, main activity during the last half hour, gender, age, height and weight as well as the main question of thermal sensation vote (TSV) in which the respondents were asked to assess their thermal sensation based on ASHRAE 7-point scale (3, cold; 2, cool; 1, slightly cool; 0, neutral; 1, slightly warm; 2, warm; 3, hot).

2.1 Additional data and data processing

Hourly data of atmospheric pressure as well as per minute data of total and diffuse solar radiation were obtained by the Institute of Environment and Sustainable Development, National Observatory of Athens (Thissio Station).
The provided data of solar radiation were used to evaluate diffuse solar radiation at the measurement site. Moreover, down-welling and up-welling long-wave radiation on a horizontal plane ($IR_{\downarrow}, IR_{\uparrow}$) were estimated using the data of $SR_{\downarrow}$, $SR_{\uparrow}$, $TR_{\downarrow}$ and $TR_{\uparrow}$. Mean radiant temperature (T_{mrt}) was calculated using the data of T_{air}, T_{globe} and WS (Thorsson et al, 2007) while the wind speed at 10 m height was estimated using the formula (Stull, 2000):

$$WS_{10m} = WS\frac{\ln(10/z_0)}{\ln(z/z_0)} \qquad (1)$$

where z is wind speed at the measured height in m, z_0 is the aerodynamic roughness length in m and was set at 0,01 m (Jendrintzky et al, 2000).
The respondents' clothing insulation (I_{cl}, in clo) and metabolic rate (M, in $W{\cdot}m^{-2}$) were estimated by the clothing description and the type of activity in accordance to ISO 9920 and ISO 8996 respectively.
A Matlab (MATLAB R2010a, The MathWorks Inc.) code was developed for the calculation of the indices COMFA, PET and UTCI consistent with weather measured data. The analysis was performed on the 3 min average of the meteorological values since that was the estimated time for completing a questionnaire.

Table 1: Assessement scale of COMFA and temperature thresholds used in PET and UTCI

Thermal Sensation	**COMFA ($W{\cdot}m^{-2}$)**	**PET (°C)**	**PET_{Med} (°C)**	**UTCI (°C)**	**TSV**
Very cold		<4	<8		-3
Cold	≤−201	4-8	8 to 12	-27 to -13	
Cool	−200 to −121	8-13	12 to 15	-13 to 0	-2
Slightly cool	−51 to −120	13-18	15 to 19	0 to 9	-1
Neutral	−50 to +50	18-23	19 to 26	9 to 26	0
Slightly warm	51 to +120	23-29	26 to 28		1
Warm	+121 to +200	29-35	28 to 34	26 to 32	2
Hot	≥+201	35-41	34 to 40	32 to 38	
Very hot		>41	>40	38 to 46	3
Extreme hot				>46	

2.2 Data analysis

The aim of the study is to evaluate the performance of COMFA, PET and UTCI consistent with weather measured data in an outdoor Mediterranean built environment. Therefore, the analysis focused on the comparison of the predictions of the three selected models with TSV. Three criteria were established: 1) the correlation between models' predictions and TSV 2) the correlation between models' class prediction and TSV and 3) the percentage of correct predictions. The first two criteria verify the model's sensibility, showing how well the model's value or class predictions vary in function to variations of TSV while they were assessed by the measure of correlation, Spearman rho, and the symmetrical measure of association, Gamma, respectively. The third criterion concerns the percentage of correct predictions, showing model's good performance, and it was validated by cross-tabulation analysis.
In order to apply the second and third criteria, the indices' assessment scales adjusted to the 7-point scale of TSV (from -3 to 3) based on the verbal description of thermal sensation. For

example, the extreme categories such as extreme hot / cold merged to the categories -3 and +3 respectively. In the case of UTCI that contain the sense of thermal stress, the assessment scale was modified according to Epstein and Moran (2006) who described thermal sensation compared to thermal physiological effects. Two assessment scales of PET were considered; the classification for Western/Middle European (PET) (Matzarakis and Mayer, 1996) as well as for the Mediterranean climate (PET_{Med}) (Cohen et al, 2013). Table 1 shows the assessment scales of the indices as well as the respective level of TSV.

3 RESULTS

Totally 313 interviews were performed in typical summer weather conditions. Air temperature ranged between 22.6 ^{o}C and 35.3 ^{o}C, relative humidity measured from 33% to 74% while the wind was kept low, apart from few gusts recorded by the anemometer. About 58% of the interviewees were males whereas 88.2% were from 18 to 64 years old indicating a very low percentage of children and elderly people in the sample. TSVs varied from -1 to +3. Some of 1.6% of the TSVs were ‘slightly cool’ while the largest percentage of votes (41%) were observed in class ‘warm’ (+2).

Table 2: Indices range during the field surveys

A Index	**Minimum**	**Maximum**	**Mean**	**Std Dev**	**B Index**	**Minimum**	**Maximum**
COMFA (W·m^{-2})	-54	288	29	66	COMFA	-1	+3
PET (^{o}C)	24.7	40.1	33.4	2.5	PET	+1	+3
UTCI (^{o}C)	26.4	36.9	33.0	1.8	PET_{Med}	0	+3
					UTCI	+2	+3

Table 2 presents indices’ range during the surveys. COMFA values ranged correctly according to TSVs, between classes -1 and +3 (Table 2B), whereas PET and UTCI range differed from that of TSV. The PET_{Med} showed better predictions (between classes 0 and +3) compared to PET, while UTCI values varied between classes +2 and +3 indicating that TSV is overestimated.

To evaluate the performance of the three models, the correlation coefficients between the models’ predictions and TSV as well as the percentage of correct predictions were estimated (Table 3). Higher correlation coefficient (0.36) was observed in the case of UTCI. The results remained the same when ranked indices values were considered. UTCI predicted with greater success the TSV (Gamma=0.45) compared to COMFA, PET and PET_{Med}, while PET_{Med} was the index with the highest percentage of correct predictions. Nevertheless the cross-tabulation of the results (Fig. 1) demonstrates reduced predictability of the models in the categories -1, 0 and 1, and apart from UTCI it is observed a tendency of thermal sensation to be classified in class +2.

Table 3: Spearman’s correlation coefficients and cross-tabulation statistics of models’ predictions and thermal sensation vote.

				Normalized values			
Index	**Correlation coefficient**	**Gamma Statistic**	**Correct predictions (%)**	**Correlation coefficient**	**Gamma Statistic**	**Correct predictions (%)**	**Total**
COMFA	0.28	0.31	15.4	0.78	0.69	0.41	1.88
PET	0.14	0.18	36.6	0.39	0.40	0.98	1.77
PET_{Med}		0.25	37.2	0.39	0.56	1.00	1.94
UTCI	0.36	0.45	33.6	1.00	1.00	0.90	2.90

In order to have an objective measure of comparison between models, the correlation coefficients and the percentage of correct predictions were normalized. As a reference value was set the maximum value per criterion. The sum of the three normalized values reveals an index on which the models can be compared and classified with respect to their applicability to Mediterranean climate (Table 3). According to our limited sample and the criteria posed in this study, UTCI showed better reproduction of TSV compared to COMFA and PET. This result is in agreement with Monteiro and Alucci (2006) who considered that is preferable to use a model with better correlation between the model and the TSV instead of using the one with the greater percentage of correct predictions because when the first model is calibrated has a good potential to correctly predict thermal sensation.

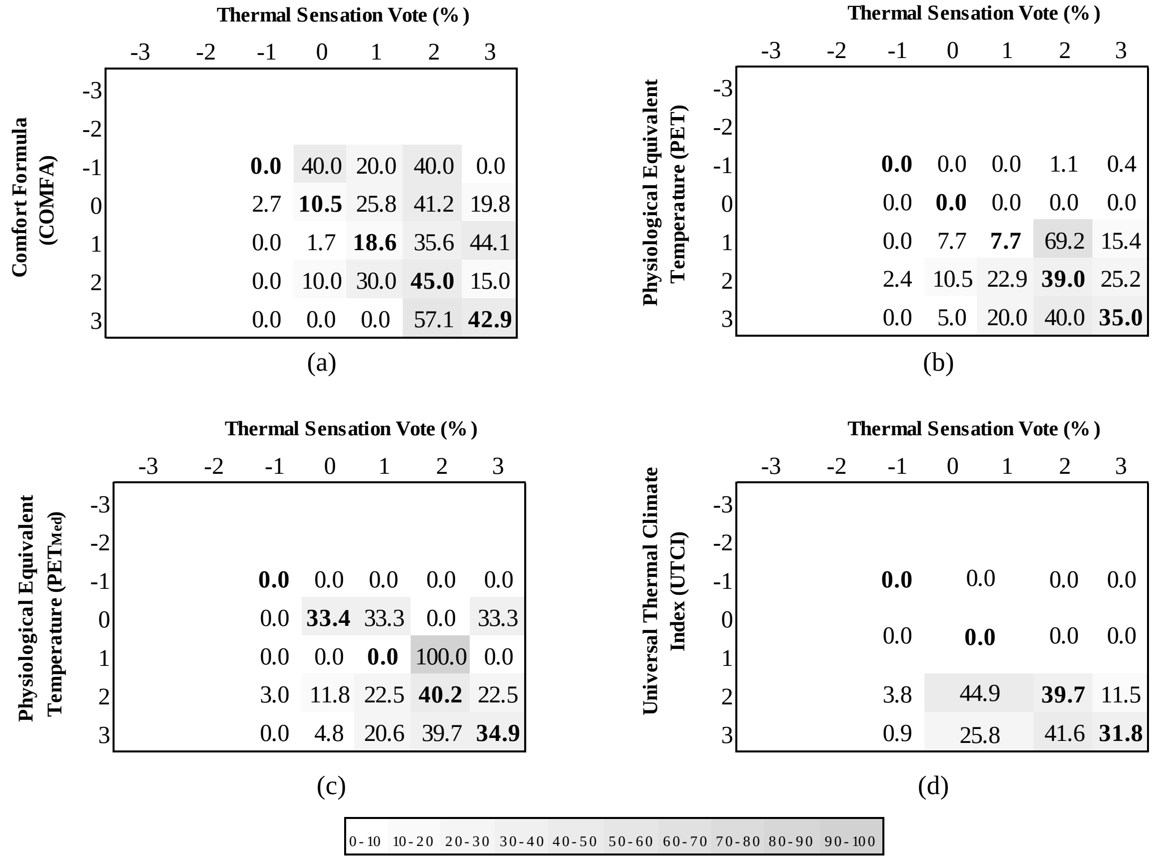

Figure 1: Distribution of predicted in relation to thermal sensation votes (each row adds to 100%)

The same method was applied considering mean TSV per 10 $W \cdot m^{-2}$ in the case of COMFA and 1^oC in the case of PET and UTCI. Spearman's correlation coefficients were estimated between rounded indices values and mean TSV at the corresponding intervals, while cross-tabulations were developed based on indices' classes and rounded mean TSV. The results are

Table 4: Spearman's correlation coefficients and cross-tabulation statistics of models' predictions and mean thermal sensation vote.

				Normalized values			
Index	**Correlation coefficient**	**Gamma Statistic**	**Correct predictions (%)**	**Correlation coefficient**	**Gamma Statistic**	**Correct predictions (%)**	**Total**
COMFA	0.45	0.28	17.2	0.47	0.28	0.31	1.05
PET	0.68	1	56.3	0.71	1.00	1.00	2.71
PET_{Med}		1	50.0	0.71	1.00	0.89	2.60
UTCI	0.96	1	27.3	1.00	1.00	0.48	2.48

are demonstrated in Table 4. PET predicted successful about 56% of mean TSV and according to the criteria posed reproduced mean TSV best of all models. The percentage of correct predictions of UTCI in the case of mean TSV (27.3%) was lower than that in the case of TSV (33.6%).

Thermal Sensation Vote (%)

Comfort Formula (COMFA)	-3	-2	-1	0	1	2	3
-3							
-2							
-1			**0.0**	0.0	0.0	0.0	0.0
0			0.0	**0.0**	18.2	72.7	9.1
1			0.0	0.0	**0.0**	85.7	14.3
2			0.0	0.0	50.0	**33.3**	16.7
3			0.0	0.0	0.0	40.0	**60.0**

(a)

Thermal Sensation Vote (%)

Physiological Equivalent Temperature (PET)	-3	-2	-1	0	1	2	3
-3							
-2							
-1			**0.0**	0.0	0.0	1.1	0.4
0			0.0	**0.0**	0.0	0.0	0.0
1			0.0	0.0	**20.0**	80.0	0.0
2			0.0	0.0	0.0	**100.0**	0.0
3			0.0	0.0	0.0	60.0	**40.0**

(b)

Thermal Sensation Vote (%)

Physiological Equivalent Temperature (PETMed)	-3	-2	-1	0	1	2	3
-3							
-2							
-1			**0.0**	0.0	0.0	0.0	0.0
0			0.0	**0.0**	50.0	50.0	0.0
1			0.0	0.0	**0.0**	100.0	0.0
2			0.0	0.0	0.0	**100.0**	0.0
3			0.0	0.0	0.0	66.7	**33.3**

(c)

Thermal Sensation Vote (%)

Universal Thermal Climate Index (UTCI)	-3	-2	-1	0–1	2	3
-3						
-2						
-1			**0.0**	0.0	0.0	0.0
0–1			0.0	**100.0**	0.0	0.0
2			0.0	60.0	**40.0**	0.0
3			0.0	0.0	100.0	**0.0**

(d)

(c)

0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100

Figure 2: Distribution of predicted in relation to mean thermal sensation votes (each row adds to 100%)

The cross-tabulation of the predicted and mean TSV showed that the range of PET (1 to 3) was in accordance with mean TSV and its predictions were improved in classes +2 and +3. COMFA tended to underestimate mean TSV, failing to successfully reproduce class +1 while UTCI tended to overestimate mean TSV reproducing fairly well the class 'neutral'.

4 CONCLUSIONS

The present study demonstrates the early results of a survey on urban thermal sensation focusing on the comparison of three outdoor thermal sensation predictive models, COMFA, PET and UTCI. According to the method followed, the criteria posed and our limited sample, UTCI showed better applicability in the case of Mediterranean climate compared to COMFA and PET while PET reproduced best of all models the mean thermal sensation vote. Nevertheless, all the models demonstrated relative low percentage of correct predictions, indicating that the calibration of the models with empirical data is possible to provide better results.

Further research should be undertaken with a larger sample size and including data from all seasons.

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