

Modeling thermal sensation in a Mediterranean climate—a comparison of linear and ordinal models

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Abstract A simple thermo-physiological model of outdoor thermal sensation adjusted with psychological factors is developed aiming to predict thermal sensation in Mediterranean climates. Microclimatic measurements simultaneously with interviews on personal and psychological conditions were carried out in a square, a street canyon and a coastal location of the greater urban area of Athens, Greece. Multiple linear and ordinal regression were applied in order to estimate thermal sensation making allowance for all the recorded parameters or specific, empirically selected, subsets producing so-called extensive and empirical models, respectively. Meteorological, thermo-physiological and overall models - considering psychological factors as well - were developed. Predictions were improved when personal and psychological factors were taken into account as compared to meteorological models. The model based on ordinal regression reproduced extreme values of thermal sensation vote more adequately than the linear regression one, while the empirical model produced satisfactory results in relation to the extensive model. The effects of adaptation and expectation on thermal sensation vote were introduced in the models by means of the exposure time, season and preference related to air temperature and irradiation. The assessment of thermal sensation could be a useful criterion in decision making regarding public health, outdoor spaces planning and tourism.

Keywords Thermal sensation · Questionnaire survey · Predictive model · Outdoor urban spaces

Introduction

Several models have been developed predicting thermal sensation. Thermal indices can be divided in four categories: (a) indices which relate only to a few meteorological parameters and they are usually applied in specific climates (direct indices) (b) indices that correlate subjective perception with the thermal conditions (empirical indices) (c) thermo-physiological indices based on heat balance equations considering the human body in a uniform environment and simulating it with one or more cylinders in order to describe its thermoregulatory responses and the heat transfer between the human body and its environment and (d) thermo-psychological indices that consider non-uniform environments and provide local and total thermal sensation of the body dividing it into several sections. The last two categories are also called rational indices (Cheng et al. 2012b).

Epstein and Moran (2006) listed about 40 indices widely used around the world and since then others have been proposed (COST Action 730 2013; Nagano and Horikoshi 2011; Monteiro and Alucci 2008). However, many of these indices were created for indoor conditions, others are difficult to understand and apply, most refer to uniform conditions, some can be used only in certain circumstances and very few take account of psychological factors that affect thermal perception (Cheng et al. 2012b). Furthermore, their predictions differ (Blazejczyk et al. 2012; Jones 2002) while they also deviate considerably from the actual thermal sensation of the population. Monteiro and Alucci (2006) calibrated a large number of indices in order to improve their predictability for the Metropolitan area of Sao Paulo, Brazil. Similar researches were conducted in different regions. Tseliou et al. (2010) attempted

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to correct three indices according to the climatic mean temperature of the region of application. Cheng et al. (2012a) concluded that Predicted Mean Vote (PMV) overestimated in summer, and underestimated in winter the thermal sensation in Hong Kong, Lin and Matzarakis (2008) proposed a new range for Physiological Equivalent Temperature (PET) for Taiwan and Pantavou et al. (2013) examining how well can the subjective thermal sensation be predicted by Universal Thermal Climate Index (UTCI) values consistent with weather measured data in the case of a Mediterranean climate, found that the cold classes of the UTCI scale were significantly lower than that of the Mediterranean.

On a different approach several researchers developed empirical thermal sensation indices based on actual sensation votes (Monteiro and Alucci 2008; Nikolopoulou and Lykoudis 2006; Stathopoulos et al. 2004). In only a few of the outdoor questionnaire surveys published for Mediterranean climates models have been developed for predicting thermal sensation. Nikolopoulou et al. (2003) proposed Actual Sensation Vote (ASV) and Ghali et al. (2011) generated the formula of Thermal Sensation (TS). In both studies the statistical analysis was performed using multiple linear regression and the models included only meteorological parameters. ASV predicts thermal sensation based on a 5-point scale while TS on a 9-point scale. Although 5-point and 7-point scales are the most common in use (Dawes 2008), 7 is considered to be the ideal number of discrete categories for describing sensation (Miller 1956) and it is used traditionally for the estimation of thermal sensation (Nicol 2008), while scales of higher precision offer no additional improvement (Dawes 2008). In that context it would be interesting to develop a thermo-physiological, 7-point scaled model of thermal sensation applicable to Mediterranean climates.

As already mentioned, in most studies of empirical indices, multiple linear regression was applied in order to predict thermal sensation even though thermal sensation was indicated by the interviewees based on a point scale (Andrade et al. 2011; Metje et al. 2008; Monteiro and Alucci 2008; Nikolopoulou and Lykoudis 2006). Thus, the dependent variable was ordinal in nature rendering the usual linear regression models possibly inappropriate, since it might be argued that the simplifying assumption of linear regression, that the dependent variable is measured on an interval scale, is not satisfied (IBM 2011). Ordinal regression, on the other hand, explicitly recognizes the ordinal nature of the dependent variable avoids arbitrary assumptions about its scale and allows testing of the assumptions regarding the probability distribution of the continuous variable that underlies the observed ordinal variable (Winship and Mare 1984).

During the year 2010–2011, a field questionnaire survey was carried out in the greater urban area of Athens, to examine the effects of meteorological, personal and psychological parameters on thermal sensation. The experimental procedure and the initial results were presented in detail in Pantavou et al. (2013). The main purpose of the present study is to

demonstrate a simple predictive thermo-physiological model for outdoor thermal sensation expressed in a 7-point scale, adjusted with psychological factors, as well as to examine the adequacy of two different methods in estimating thermal sensation: ordinary linear and ordinal regression. This model development procedure elucidates the significance of each variable to the determination of thermal sensation in Mediterranean climates and the applicability of each model fitting method.

Materials and methods

Study area

Athens is the capital of Greece and one of the most distinguished travel destinations in the world. The urban area of Athens extends beyond the boundaries of the municipality of Athens to Piraeus, the main port of Greece and one of the largest in the world concerning passenger traffic (PPA S.A. 2013). Around one third of the Greek population lives in the larger urban area of Athens. The climate is Mediterranean while the climatological mean minimum and maximum temperatures (1961–1990) are 22.5 °C and 32.6 °C respectively for July (the hottest month of the year), as well as 6.5 °C and 12.9 °C for January (the coldest month of the year) (NOA-IERSD 2013). The questionnaire survey was carried out at two sites in the center of Athens and in a coastal location within the larger urban area of Athens in order to capture different microclimates: Syntagma square, the most central square of the city with green areas and a water fountain in the centre; Ermou Street, a pedestrian street canyon (width 10 m, length 200 m, height 20 m) next to Syntagma square; and Flisvos coast located about 6 km south of the center of Athens and 4 km southeast of Piraeus.

Data

The field surveys involved microclimatic measurements along with structured interviews of the users of the site during a total of 16 days in July, October and February 2010–2011. Field surveys were conducted for 2 days per season at each site, one day during morning-midday and one during afternoon–evening–night in order to collect data for the entire day. Their duration changed over season for security reasons as it was getting dark earlier in autumn and winter than in summer. The surveys started at about 10:00 am and run until 22:00 in summer and 19:30 in autumn and winter. Due to low attendance, no measurements were performed in Flisvos coast during winter and autumn afternoon, whereas an additional survey was performed in Syntagma during winter to obtain a number of questionnaires closer to the other seasons. Spring was excluded as a transient season with similar thermal

conditions to autumn (October). A detailed list of the surveys conducted can be found in Table 1.

A Rotronic S3CO3 thermo-hygrometer equipped with a non-ventilated radiation shield of aluminum, a Second Wind C3 anemometer, two Kipp & Zonen CM3 pyranometers and an ECO pyrgeometer were used to monitor air temperature (T_{air}), relative humidity (RH), average and maximum wind speed (WS, WS_{max}), downwelling (SR_{\downarrow}) and reflected (SR_{\uparrow}) solar radiation as well as downwelling and ground total radiation (TR_{\downarrow} , TR_{\uparrow}) on a horizontal plane. A PVC sphere, 40 mm diameter painted grey, with an emissivity of 0.3 and response time less than 4 min (Nikolopoulou et al. 1999) was used to measure globe temperature (T_{globe}). All sensors were placed on a mobile tripod at the height of 1.1 m above the ground. The data were stored on a CR10X Campbell Scientific data logger at 1 min intervals. Ground surface temperature (T_{ground}) was measured using an Infrared Thermometer at three points close and around the interviewee, at the onset of each interview.

The questionnaire consisted of the main question asking for the subjective assessment of thermal sensation based on ASHRAE 7-point scale (−3 - cold, −2 - cool, −1 - slightly cool, 0 - neutral, 1 - slightly warm, 2 - warm, 3 - hot), namely thermal sensation vote (TSV). Moreover it included questions about personal characteristics of the respondents such as gender, age, main activity during the last half hour, clothing, position in relation to the sun (shading), exposure time (visit duration at the interview site - ‘For how long have you been in this site?’) and exposure history (whether or not the respondents were in an air-conditioned environment before their visit to the interview site), medical history, smoking and health status as well as questions related to psychological factors that

may have an effect on thermal sensation such as season, time of the day, companionship (whether or not the respondents were alone at the interview site), recent experience (place respondents’ were before their visit to the interview site), visit purpose, overall comfort (satisfaction in relation to the overall environment), preference related to overall sensation and the way it would be improved (changing air temperature, humidity, wind, irradiation) (Table 2). The interviewees were randomly selected.

The recorded radiation data SR_{\downarrow} , SR_{\uparrow} , TR_{\downarrow} and TR_{\uparrow} were used to calculate the long-wave radiation on a horizontal plane (IR_{\downarrow} , IR_{\uparrow}) while mean radiant temperature (T_{mrt}) was estimated by T_{air} , T_{globe} and WS (Thorsson et al. 2007). Furthermore thermal insulation of clothing (I_{cl}), and metabolic rate (M) were estimated using the descriptions of the clothes and the activity stated in the questionnaire in accordance with ISO 9920 and 8996 (ISO 1993, 2004). Body surface (A_{du}) was calculated from the height and weight of the respondents using the formula of DuBois and DuBois (1916). The atmospheric pressure used for Syntagma and Ermou comes from the Thissio meteorological station of the National Observatory of Athens, Institute for Environmental Research and Sustainable Development, (NOA-IERSD) and from Hellinikon meteorological station of the Hellenic National Meteorological Service (HNMS) for the case of Flisvos coast.

The original 1-min data were checked for apparent inconsistencies that led to less than 0.5 % of the values being rejected and then aggregated into 3 min averages, since that was the estimated time for completing a questionnaire. The whole sample was used while the overall completeness of the data corresponded to 99.1 %.

Data analysis

Trying to find the most suitable method to predict thermal sensation vote (TSV), linear and ordinal logistic regression were applied to meteorological, personal and psychological variables separately, to produce meteorological, personal and psychological models, as well as the combination of meteorological and personal variables to produce the thermophysiological models. Ordinal regression is an extension of generalized linear models for ordinal data which estimates the probability of observing a particular class or lower. The independent variables can be either continuous or categorical while in the case of categorical variables a reference category should be defined. The method produces a set of equations, one for each class of the dependent ordinal variable, providing the cumulative probability of occurrence up to this class. The probability of each class is calculated by the difference of the cumulative probabilities of two consecutive classes. The class predicted by the model is the one with the highest probability.

In order to establish a useful model for predicting TSV, some of the original classes -according to the questionnaire- of

Table 1 Dates and time frames of the surveys

	Date	Time	Site
Summer	15 July 2010	16:45–19:30	Syntagma
	16 July 2010	16:00–20:39	Ermou
	17 July 2010	19:13–21:51	Flisvos
	18 July 2010	11:33–13:50	Flisvos
	20 July 2010	10:05–15:18	Syntagma
	21 July 2010	10:40–14:06	Ermou
	Autumn	16 October 2010	10:21–15:05
17 October 2010		11:03–15:09	Syntagma
20 October 2010		16:15–19:30	Syntagma
23 October 2010		16:23–19:20	Ermou
24 October 2010		13:54–15:57	Flisvos
Winter	09 February 2011	15:23–19:40	Ermou
	12 February 2011	11:18–15:40	Ermou
	13 February 2011	11:35–14:00	Syntagma
	26 February 2011	16:00–18:30	Syntagma
	27 February 2011	11:59–15:00	Syntagma

Table 2 The collected and estimated data used in the analysis divided into meteorological, personal and psychological parameters

Measured parameters	Questionnaire parameters	
	Personal	Psychological
T_{air} (°C)	Age (<12/13–17/18–24/25–34/35–44/45–54/55–64/>65)	Season (Warm/Transitional/Cold)
RH (%)	Gender	Time of day (Morning/Midday/Afternoon/Evening/Night)
WS ($m \cdot s^{-1}$)	Height	Companionship (alone/with company) ^f
WS_{max} ($m \cdot s^{-1}$)	Weight	Place of residence (city center/city suburb/province)
SR_{\downarrow} ($W \cdot m^{-2}$)	Body surface	Place before exposure (indoors/transportation/outdoors) ^g
SR_{\uparrow} ($W \cdot m^{-2}$)	Activity – Metabolic rate ($W \cdot m^{-2}$) (calm/in motion) ^a	Visit purpose (work/passing by/entertainment) ^h
IR_{\downarrow} ($W \cdot m^{-2}$)	Clothing Clothing insulation (clo)	Overall comfort (uncomfortable/neutral/comfortable) ⁱ
IR_{\uparrow} ($W \cdot m^{-2}$)	Glasses (yes/no)	Weather opinion Temperature (cool/neutral/warm)
T_{globe} (°C)	Scarf (yes/no)	Humidity (humid/neutral/dry)
T_{ground} (°C)	Color (dark/light)	Wind speed (windy/neutral/calm)
T_{mrt} (°C)	Shading (under the sun/shade of a building/no sun) ^b Exposure time (<5 min/5 min to 1 h/>1 h) ^c Air conditioning (yes/no) Medical history (no medical history/with a medical history) ^d Health status (as usual/better than usual/worse than usual) Smoking status (non-smoker/smoker) ^e	Preference Overall sensation (cooler/no change/warmer) Temperature (higher/no change/lower) Humidity (higher/no change/lower) Wind speed (higher/no change/lower) Irradiance (higher/no change/lower)

^a calm = Sleeping/Sitting/Standing, in motion = Walking/Sports

^b under the sun = whole or part of the body exposed to the sun/shade of a tree, no sun = cloudy weather/night

^c 5min to 1 h = 5 to 15 min/15 to 30 min/30 min to 1 h

^d no medical history = none, with a medical history = Asthma/respiratory/cardiovascular/allergy

^e non-smoker = never smoked/former smoker, smoker = current smoker

^f with company = with 1 person/with 2 persons or more

^g indoors = home/at work/other indoor place, transportation = car/public transportation

^h entertainment = rest/shopping/meeting friends

ⁱ uncomfortable = very uncomfortable/uncomfortable, comfortable = comfortable/very comfortable

the independent categorical variables were merged. The criterion considered was that of separability according to ANOVA and cross-tabulation analyses as well as the nature of the parameters (Table 2).

First, the independent variables were checked for possible correlations between them, so as to avoid problems of multicollinearity. Linear and ordinal regression on TSV were applied for each independent variable individually. The

independent variables that showed no significant correlation with TSV were excluded from further analysis. For the final stage of model development, selection among the remaining variables was based on avoiding multicollinearity and the physical significance of the parameters. In the case of categorical independent variables, in the model remained those with at least one class having a statistically significant correlation with the reference category and the significance level for that parameter being <0.05 in a univariate ANOVA test. Categorical predictor variables were dummy coded in order to be entered into the linear regression model. A categorical variable with k levels was transformed into k-1 variables each with two levels (0–1). The regression equation was then formed as:

$$y' = b_0 + a_1 \cdot D_1 + a_2 \cdot D_2 + 2 \dots a_{k-1} D_{k-1} + b_1 \cdot x_1 + b_2 \cdot x_2 + \dots + b_v \cdot x_v \tag{1}$$

where D the categorical variable with D₁=1 when level 1 was valid and D₁=0 when any of the other levels were valid, a₁, a₂, ... a_{k-1} coefficients of each level of the categorical variable, x₁, x₂, ..., x_v the continuous variables and b₁, b₂, ..., b_v the coefficients of the continuous variables.

Three types of models were developed: one that included only the meteorological parameters (meteo), one that included only the personal parameters (personal) and one including meteorological and personal parameters, named thermo-physiological model (T/P).

Thereafter the thermo-physiological model was corrected by the psychological factors. First, the difference between TSV and thermo-physiologically predicted TSV was calculated (DTSV = TSV-thermo-physiologically predicted TSV). The dependence of DTSV on the psychological factors was then examined producing the predicted DTSV. The final

model resulted from the addition of thermo-physiologically predicted TSV and the predicted DTSV. This process yielded what were termed as ‘extensive models’, considering all the experimental parameters, one using linear and another using ordinal regression. The process was repeated selecting only those parameters theoretically expected to affect thermal sensation, namely T_{air}, T_{mrt}, WS, RH, I_{cl} and M (Macpherson 1962; Jones 2002). This resulted in two ‘empirical’ models a linear and an ordinal one.

The statistical analysis was carried out using SPSS 17.0 (SPSS Inc, 2008). All results presented below are statistically significant at a confidence level equal to or less than 0.05 (Sig ≤0.05).

Results

The 1706 interviews of the survey were performed in a variety of outdoor environmental conditions (Table 3). Mean air temperature by season ranged 4–5 °C above the respective climatological means (1961–1990) (NOA-IERSD 2013) while wind speed was generally low except for some gusts. In summer the recorded wind velocities were higher than autumn and winter. Some 55 % of the interviewees were males, whereas about 90 % were between 18 and 64 years of age indicating a lower than expected percentage of children and elderly people – accounting for 35 % of the area’s population according to the latest available census (Hellenic Statistical Authority 2013). Males’ average height and weight were 1.77 m 80 kg while females’ were 1.66 m 60 kg approaching the average man and woman (ISO 8996 2004). Almost 45 % of the interviews were conducted in summer.

Table 3 Meteorological conditions during the field surveys

	Summer				Autumn				Winter			
	Min	Max	Mean	StDev	Min	Max	Mean	StDev	Min	Max	Mean	StDev
T _{air} (°C)	22.6	39.3	33.2	1.5	16.9	28.6	22.7	3.0	7.1	20.5	13.6	4.5
RH (%)	22	74	38	6	42	74	60	7	33	79	61	13
WS (m·s ⁻¹)	0.3	9.3	1.1	0.9	0.3	2.6	0.4	0.3	0.3	2.0	0.8	0.4
WS _{max} (m·s ⁻¹)	0.3	15.2	2.0	1.7	0.3	3.1	0.7	0.5	0.3	3.1	1.3	0.8
SR _↓ (W·m ⁻²)	0	924	236	277	0	670	186	227	0	640	139	211
SR _↑ (W·m ⁻²)	0	274	58	69	0	199	44	64	0	151	27	41
IR _↓ (W·m ⁻²)	5	763	460	92	122	786	418	58	85	419	384	36
IR _↑ (W·m ⁻²)	426	739	563	37	395	575	486	32	308	494	430	26
T _{globe} (°C)	24.4	43.8	35.8	3.1	17.6	37.1	25.6	5.0	8.2	28.3	15.8	5.9
T _{mrt} (°C)	24.6	44.7	36.3	3.4	17.7	38	26	5.3	8.5	29.1	16.3	6.0
T _{ground} (°C)	18.0	54.0	35.6	4.7	14.0	34.0	21	3.6	6.0	24.0	9.6	3.7
P (hPa)	996.5	1008.4	1001.0	3.8	996.5	1008.6	1001.2	4.6	1000.6	1004.0	1002.5	0.7

Univariate linear and ordinal regression analyses between TSV and the explanatory variables showed that all meteorological parameters had statistically significant relationship with TSV. The personal parameters: gender, age, weight, height, body surface, smoking status as well as the psychological factors of opinion on RH and WS, and residence were found to be uncorrelated with TSV so they were excluded from further analysis. Although according to regression analysis T_{globe} , T_{mrt} and T_{ground} have an effect on TSV, these were also excluded from the modeling in order to avoid problems of multicollinearity. Pearson's correlation test showed a strong relationship between T_{air} and T_{globe} (0.98) as well as T_{air} and T_{mrt} (0.97), so only T_{air} was used in the model since it is easier to measure and with greater accuracy than T_{globe} or T_{mrt} .

Strong correlation was also observed between IR_{\uparrow} and T_{ground} (0.84). The IR_{\uparrow} was chosen to be included in the model because the measurement of T_{ground} involves greater uncertainty. Also the personal parameters of the additional clothing, sunglasses, and gloves were excluded because they were meaningful only for a specific season.

Extensive model

Linear regression analysis

Considering only the meteorological parameters, the TSV can be estimated by the following formula (standard errors of the parameters in Table 4a):

$$LRP_{\text{meteo}}^{\text{ext}} = 50.7 + 0.112 \cdot T_{\text{air}} - 0.018 \cdot RH - 0.10 \cdot WS + 0.001 \cdot SR_{\downarrow} - 0.002 \cdot IR_{\uparrow} - 0.05 \cdot P \quad (R^2 = 0.65) \quad (2)$$

Table 4 Regression coefficients of simple linear regression prediction models for thermal sensation vote

Models	A Coeff	LRP _{meteo} ^{ext} Std Err	B Coeff	LRP _{personal} ^{ext} Std Err	C Coeff	LRP _{T/P} ^{ext} Std Err	D Coeff	LRP _{T/P} ^{emp} Std Err
Constant	50.7	8.2	2.5	0.1	29.3	9.2	-2.3	0.2
T_{air}	0.112	0.008			0.088	0.008		
RH	-0.018	0.004			-0.013	0.004		
WS	-0.10	0.03			-0.08	0.03	-0.11	0.03
SR_{\downarrow}	0.001	0.000			0.001	0.000		
SR_{\uparrow}					-0.002	0.001		
IR_{\uparrow}	-0.002	0.001						
T_{mrt}							0.120	0.004
P	-0.05	0.01			-0.030	0.009		
I_{cl}			-2.2	0.1	-0.4	0.1	-0.4	0.1
Shading								
No sun			-1.45	0.07	-0.5	0.08		
Shade of a building			-0.60	0.06	-0.14	0.06		
Under the sun			0		0			
Exposure time								
< 5 min			0.16	0.07	0.20	0.06		
5 min to 1 h			0.01*	0.06	0.10	0.05		
> 1 h			0		0			
Clothing color								
Dark			-0.16	0.05				
Light			0					
Air conditioning								
Yes			0.14	0.06				
No			0					
Health status								
Worse than usual			0.4	0.1				
As usual			0.08*	0.10				
Better than usual			0					

*Sig > 0.05

where LRP_{meteo}^{ext} is Linear Regression Prediction of TSV by meteorological parameters while the superscript ext stands for extensive model, T_{air} is in °C, RH in %, WS in $m \cdot s^{-1}$, SR_{\downarrow} , IR_{\uparrow} in $W \cdot m^{-2}$ and P in hPa.

The values generated from Eq. 2 are continuous. In order to test the correspondence between TSVs and the respective predicted votes (LRP_{meteo}^{ext}), the latter were classified into seven categories using simple rounding to the nearest integer and further assigning values greater than +3 to +3 and lower than -3 to -3. Figure 1a demonstrates the cross-tabulation of TSVs and ranked LRP_{meteo}^{ext} . The symmetrical measure of association, Gamma was used as an index of agreement. The

linear meteorological model predicts TSV classes fairly well (Gamma=0.81) showing reduced predictability in the categories -3, -2, +2.

The linear personal model, $LRP_{personal}^{ext}$ (Linear Regression Prediction of TSV by personal parameters in the case of extensive model) indicates the most important personal parameters (Table 4b). The dominant personal factors when combined with the meteorological variables to produce a thermo-physiological model were I_{cl} , shading and exposure time. The linear thermo-physiological model ($LRP_{T/P}^{ext}$) is presented in Eq. 3 (standard errors of the parameters in Table 4c):

$$LRP_{T/P}^{ext} = 29.3 + 0.088 \cdot T_{air} - 0.013 \cdot RH - 0.08 \cdot WS + 0.001 \cdot SR_{\downarrow} - 0.002 \cdot SR_{\uparrow} - 0.030 \cdot P - 0.4 \cdot I_{cl} - 0.50 \cdot S_1 - 0.14 \cdot S_2 + 0.20 \cdot E_1 + 0.10 \cdot E_2 \quad (3)$$

$$(R^2 = 0.67)$$

where $LRP_{T/P}^{ext}$ is Linear Regression Prediction of TSV by thermo-physiological parameters for extensive model, T_{air} is in °C, RH in %, WS in $m \cdot s^{-1}$, SR_{\downarrow} , IR_{\uparrow} in $W \cdot m^{-2}$ and P in hPa, I_{cl} in clo,

$$S_1 = \begin{cases} 1 & \text{if shading = no sun} \\ 0 & \text{if shading = shade of a building/under the sun,} \end{cases}$$

$$S_2 = \begin{cases} 1 & \text{if shading = shade of a building} \\ 0 & \text{if shading = no sun/under the sun,} \end{cases}$$

$$E_1 = \begin{cases} 1 & \text{if exposure time} \leq 5 \text{ min} \\ 0 & \text{if exposure time} > 5 \text{ min,} \end{cases}$$

$$E_2 = \begin{cases} 1 & \text{if } 5 \text{ min} < \text{exposure time} < 1 \text{h} \\ 0 & \text{if exposure time} \leq 5 \text{ min or } \geq 1 \text{h} \end{cases}$$

The Gamma statistic (0.82, $p < 0.001$) suggests that the predictions of the thermo-physiological model were slightly improved in relation to those of the meteorological model.

Nevertheless the cross-tabulation of the results (Fig. 1b) shows that the model classified all cases in the middle five categories, therefore it cannot be considered as successful.

Ordinal regression analysis

Applying ordinal regression to the meteorological parameters resulted that the model included the same parameters with the linear one while the cross-tabulation of the results (Fig. 1c) (Gamma=0.80) indicated that the ordinal model produces improved predictions of thermal sensation in categories -2, +2 and +3. The ordinal regression prediction of TSV by meteorological parameters (ORP_{meteo}^{ext}) can be estimated according to the method described in the Appendix. The cumulative probabilities were calculated according to Eq. (4) (standard errors of the parameters in Table 5a):

$$\begin{aligned} P(\leq -3) &= \{1 + \exp[-(-101.0 - (0.24 \cdot T_{air} - 0.035 \cdot RH - 0.22 \cdot WS + 0.002 \cdot SR_{\downarrow} - 0.004 \cdot IR_{\uparrow} - 0.10 \cdot P))]\}^{-1} \\ P(\leq -2) &= \{1 + \exp[-(-99.4 - (0.24 \cdot T_{air} - 0.035 \cdot RH - 0.22 \cdot WS + 0.002 \cdot SR_{\downarrow} - 0.004 \cdot IR_{\uparrow} - 0.10 \cdot P))]\}^{-1} \\ P(\leq -1) &= \{1 + \exp[-(-97.0 - (0.24 \cdot T_{air} - 0.035 \cdot RH - 0.22 \cdot WS + 0.002 \cdot SR_{\downarrow} - 0.004 \cdot IR_{\uparrow} - 0.10 \cdot P))]\}^{-1} \\ P(\leq 0) &= \{1 + \exp[-(-94.9 - (0.24 \cdot T_{air} - 0.035 \cdot RH - 0.22 \cdot WS + 0.002 \cdot SR_{\downarrow} - 0.004 \cdot IR_{\uparrow} - 0.10 \cdot P))]\}^{-1} \\ P(\leq 1) &= \{1 + \exp[-(-93.1 - (0.24 \cdot T_{air} - 0.035 \cdot RH - 0.22 \cdot WS + 0.002 \cdot SR_{\downarrow} - 0.004 \cdot IR_{\uparrow} - 0.10 \cdot P))]\}^{-1} \\ P(\leq 2) &= \{1 + \exp[-(-91.2 - (0.24 \cdot T_{air} - 0.035 \cdot RH - 0.22 \cdot WS + 0.002 \cdot SR_{\downarrow} - 0.004 \cdot IR_{\uparrow} - 0.10 \cdot P))]\}^{-1} \\ P(\leq 3) &= 1 \end{aligned} \quad (4)$$

The probability of each TSV category was computed by the subtraction of the cumulative probability per two consecutive classes (e.g. $P(3) = P(\leq 3) - P(\leq 2)$). The ORP_{meteo}^{ext} category was the one with the maximum probability.

The parameters that remained in the ordinal personal model ($ORP_{personal}^{ext}$) (Table 5b) were the same with the linear personal model ($LRP_{personal}^{ext}$) with the addition of clothing color. The thermo-physiological ordinal model

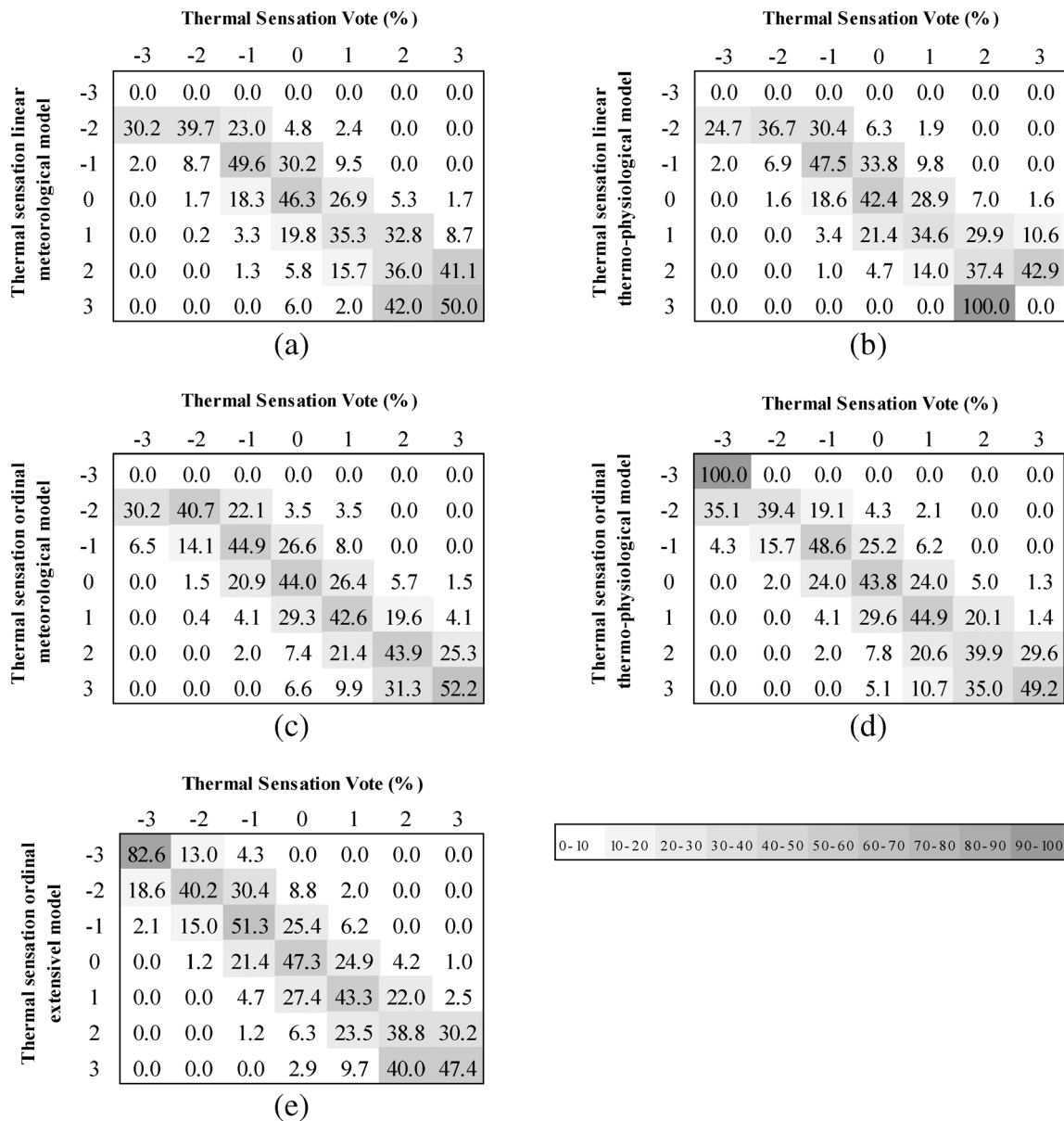


Fig. 1 Reproduction of the thermal sensation vote by the linear and ordinal extensive models. Distribution of predicted in relation to thermal sensation votes (each row adds to 100 %)

($ORP_{T/P}^{ext}$) (Table 5c) reproduced TSVs slightly better than the ordinal meteorological model (ORP_{meteo}^{ext}) ($\Gamma=0.82$) (Fig. 1d) predicting cases in class -3. In comparison with the respective linear, the thermo-physiological ordinal model included the same parameters and Gamma statistics, while it reproduced the extreme categories with greater success.

Final model

Concluding that the ordinal thermo-physiological model (Table 5c) provides the best overall predictions of TSVs, an attempt was made to further improve this model assuming that psychological factors may account for, at least a part of, the

deviation between the predicted and the TSV. Thus, the difference of thermal sensation vote and the ordinal thermo-physiologically predicted thermal sensation vote was estimated ($DTSV=TSV-ORP_{T/P}^{ext}$). Then univariate ordinal regression analysis was performed between the DTSV and the psychological parameters. No statistically significant correlation was identified between DTSV and visit purpose, companionship, region of residence, the place that people were before they visited the experimental site (recent experience), people’s opinion about RH, weather’s suitability for activity and people’s preference in relation to RH. The model of $DTSV^{ext}$ is presented in Table 6a.

The effect of psychological factors on TSV were taken into account in the final model (ORP_{final}^{ext}) by adding the

Table 5 Regression coefficients of ordinal regression prediction models for thermal sensation vote

Models	A Coeff	ORP _{meteo} ^{ext} Std Dev	B Coeff	ORP _{personal} ^{ext} Std Dev	C Coeff	ORP _{T/P} ^{ext} Std Dev	D Coeff	ORP _{T/P} ^{emp} Std Dev
Cold=-3	-101.0	17.4	-8.9	0.3	-55	20	0.02*	0.4
Cool=-2	-99.4	17.4	-7.4	0.2	-54	20	1.6	0.4
Slightly cool=-1	-97.0	17.3	-5.3	0.2	-51	20	3.9	0.4
Neutral=-0	-94.9	17.3	-3.4	0.2	-49	20	6.1	0.4
Slightly warm=+1	-93.1	17.3	-1.9	0.1	-47	20	7.9	0.4
Warm=+2	-91.2	17.3	-0.4	0.1	-45	20	9.7	0.4
Hot=+3	0		0		0		0	
T _{air}	0.24	0.02			0.19	0.02		
RH	-0.035	0.07			-0.025	0.008		
WS	-0.22	0.06			-0.20	0.07	-0.25	0.06
SR _↓	0.002	0.000			0.003	<0.001		
SR _↑					-0.005	0.002		
IR _↑	-0.004	0.002						
T _{mrt}							0.25	0.01
P	-0.10	0.02			-0.05	0.02		
I _{cl}			-4.1	0.3	-0.8	0.3	-0.7	0.2
Shading								
no sun= 1			-2.6	0.1	-1.2	0.2		
shade of a building= 2			-1.1	0.1	-0.3	0.1		
under the sun= 3			0		0			
Exposure time								
< 5 min= 1			0.3	0.1	0.3	0.1		
5 min to 1 h= 2			0.06*	0.11	0.2*	0.1		
> 1 h= 3			0		0			
Clothing color								
dark= 1			0.2	0.1				
light= 2			0					

*Sig >0.05

predicted DTSV (DTSV^{ext}) to the ORP_{T/P}^{ext} (ORP_{final}^{ext}=ORP_{T/P}^{ext}+DTSV^{ext}). The cross-tabulation of the results shows that the resulting model reproduces fairly well thermal sensation vote (Gamma=0.83) even in the extreme categories (Fig. 1e).

Empirical model

Linear regression analysis

An empirical thermo-physiological model was established using as independent variables T_{air}, T_{mrt}, RH, WS, I_{cl} and M. According to the linear thermo-physiological model, TSV can be estimated according to the equation (standard errors of the parameters in Table 4d):

$$LRP_{T/P}^{emp} = -2.3 + 0.120 \cdot T_{mrt} - 0.11 \cdot WS - 0.4 \cdot I_{cl} \quad (5)$$

$(R^2 = 0.65)$

where LRP_{T/P}^{emp} is Linear Regression Prediction of TSV by thermo-physiological parameters while the superscript emp stands for empirical model, T_{mrt} is in °C, WS in m·s⁻¹, I_{cl} in clo.

Interestingly, air temperature and relative humidity were not included in the model. The model indicated mean radiant temperature as the most important meteorological variable in the determination of TSV in accordance to Mayer (1993). Although the WS variation during the measurements was low, WS remained in the model. We also note that the correlation coefficient (0.65) is practically the same as the corresponding extensive model (LRP_{T/P}^{ext}), while the respective cross-tabulation (Fig. 2a) produced an identical Gamma measure of symmetry (0.82). Observing Fig. 2a more closely, we see that the percentage of correctly predicted TSV is higher in the warmer categories in relation to the corresponding extensive model.

Ordinal regression analysis

The ordinal thermo-physiological model $ORP_{T/P}^{emp}$ (Table 5d) includes the same parameters as the corresponding empirical linear model ($LRP_{T/P}^{emp}$), while the cross-tabulation gives almost the same Gamma statistic (0.81) with the linear model but behaves even better in the extreme categories of thermal sensation.

However, both linear and ordinal empirical models do not produce values in the category -3 .

Final model

The overall empirical model (ORP_{final}^{emp}) corrected for psychological effects, was finally composed based on the ordinal thermo-physiological empirical model. Following the same method as in the extensive model, the difference of TSV minus the $ORP_{T/P}^{emp}$ ($DTSV' = TSV - ORP_{T/P}^{emp}$), was estimated. Ordinal regression was applied between $DTSV'$ and those subjective psychological factors not related with personal opinion or preference. The analysis showed that $DTSV'$ was related with season and purpose of visit (Table 6b). Adding the $ORP_{T/P}^{emp}$ and the predicted DTSV ($DTSV^{emp}$), results in the overall empirical model ($ORP_{final}^{emp} = ORP_{T/P}^{emp} + DTSV^{emp}$). The cross tabulation of the ORP_{final}^{emp} (Fig. 2c) demonstrates an improvement in relation to the empirical thermo-physiological model ($ORP_{T/P}^{emp}$) albeit worse performance compared to the extensive overall model (ORP_{final}^{ext}) (Gamma=0.82), notably not classifying any cases as cold (-3).

Overview of the models' parameters

The main meteorological parameters affecting thermal sensation were T_{air} and WS. RH showed a negative effect on TSV in accordance to Givoni et al. (2003) and Nikolopoulou (2004) although in other studies a positive effect was identified (Monteiro and Alucci 2008). The personal models demonstrated that recent thermal experience and health status affect TSV as well highlighted the important role of adaptation and physical fitness. People previously exposed in a controlled environment or with a health status- on the day of the interview- 'worse than usual' felt 'warmer' in relation to those who were in a non air-conditioned place or their health status was 'better than usual'. However one reason for these results could be the unbalanced distribution of questionnaires towards mild and hot season when people's thermal discomfort may be expressed by voting higher classes of thermal sensation scale. The main personal parameters that also remained in the thermo-physiological models were I_{cl} , shading and exposure time. The interviewees reported higher classes of TSVs as I_{cl} decreased in agreement with the UTCI-clothing model (Havenith et al. 2012) which indicated that I_{cl} decreased with rising air temperature. The respondents who were exposed to the sun during the interview

Table 6 Regression coefficients of psychological parameters in Ordinal Regression Prediction models for the difference of thermal sensation vote and thermo-physiological ordinal regression prediction of thermal sensation vote (DTSV)

Models	A Coeff	DTSV ^{ext} Std Dev	B Coeff	DTSV ^{emp} Std Dev
DTSV= -3	-3.4	0.0	-4.8	0.2
DTSV= -2	-1.6	0.2	-3.3	0.1
DTSV= -1	0.4	0.2	-1.4	0.1
DTSV= -0	2.8	0.2	0.6	0.1
DTSV= $+1$	4.9	0.3	2.8	0.1
DTSV= $+2$	6.9	0.4	5.0	0.4
DTSV= $+3$	0		0	
Season				
Summer=1	-1.6	0.2	-0.6	0.1
Autumn=2	-0.5	0.1	-0.4	0.1
Winter=3	0		0	
Overall comfort				
Uncomfortable= -1	0.4	0.1		
Neutral=0	0.1*	0.1		
Comfortable=1	0			
Sensation preference				
Cooler= -1	0.9	0.3		
No change=0	0.2*	0.2		
Warmer=1	0			
Air temperature preference				
Lower= -1	1.0	0.3		
No change=0	0.7	0.2		
Higher=1	0			
Irradiation preference				
Lower= -1	0.9	0.3		
No change=0	0.7	0.2		
Higher=1	0			
Visit purpose				
Work=1			-0.2	0.1
Passing by=2			-0.05^*	0.2
Entertainment=1			0	

*Sig >0.05

or those who were at the site of the interview less than 5 min indicated higher classes of TSV compared to those who were not exposed to the sun or were at the site of the interview for more than 1 h. Metabolic rate was not retained in the model even though in the context of metabolic heat production it is an important factor of the heat balance equation (Fanger 1970; Katavoutas et al. 2009) and expectedly of thermal sensation. However, the context of the experiment narrowed the variation of this parameter and as a result it appears to have an insignificant effect on pedestrian TSV.

The deviation of predicted TSV by the extensive and empirical thermo-physiological models from the TSV

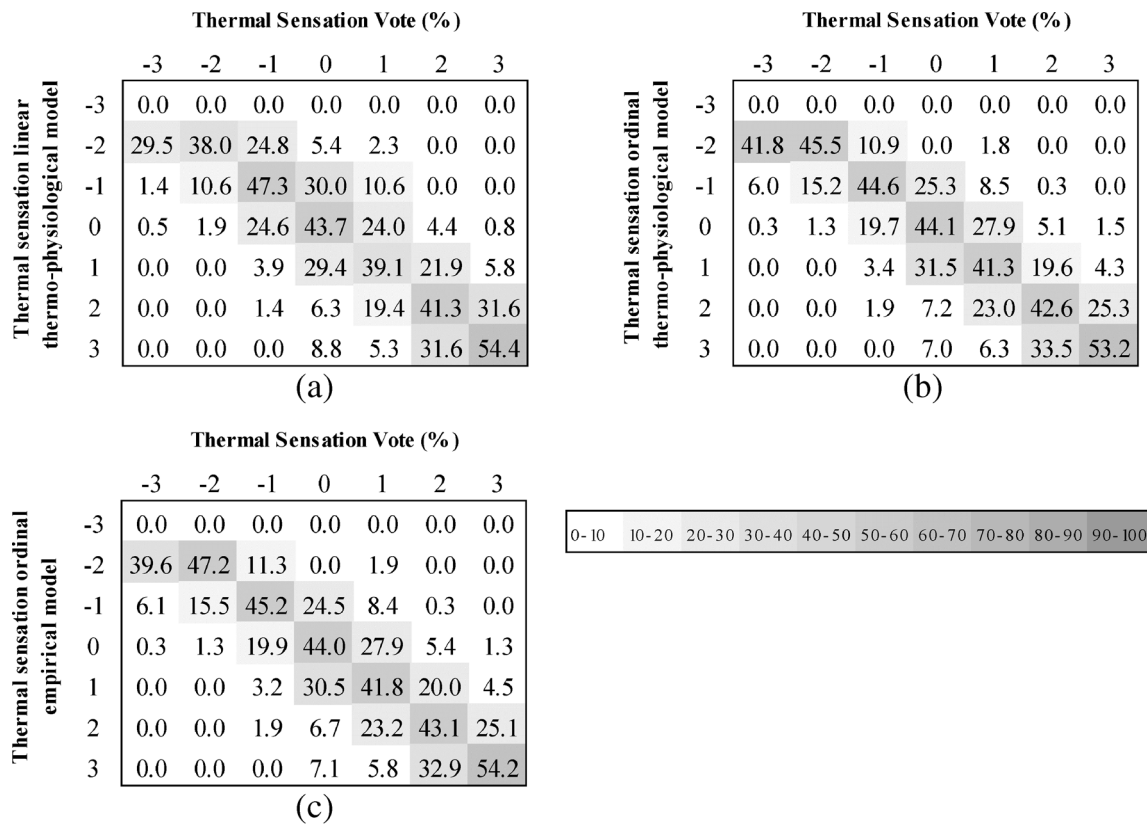


Fig. 2 Reproduction of the thermal sensation vote by the linear and ordinal empirical models. Distribution of predicted in relation to thermal sensation votes (each row adds to 100 %)

may be justified by psychological factors. In summer and in autumn the predicted TSVs were higher than TSVs and these differences were larger than those in winter indicating that the variation may be attributed to expectation. The extensive model showed that the abovementioned deviation was biased by overall comfort at the site of the interview and preference. The dominant preference variables were those related to air temperature and irradiation. The empirical model indicated that the purpose of visit stimulated predicted TSVs higher than the respective TSVs. This could be attributed to adaptation as visitors with a purpose (usually work) remained on site for longer periods than those being there for fun or simply passing by.

Conclusions

This study demonstrates the methodology and the evaluation of modeling outdoor pedestrian thermal sensation in order to extend our knowledge in the case of the urban Mediterranean climates and to examine the appropriateness of using linear and ordinal regression for the statistical analysis. The predictive models arose using data of a field survey where people were asked to indicate their thermal sensation and were

interviewed in personal and psychological inquiries while there were in situ measurements of meteorological parameters.

The interviews carried out under normal conditions for each of the three seasons, warm, cool, and transitional. The study area included three different locations, a square, a street canyon and a coastal area in the larger urban area of Athens. People who participated in the study were in the majority healthy and their activity was moderate.

The thermal sensation of the respondents’ was influenced by weather and personal factors while the deviation of the actual from the predicted thermal sensation was affected by psychological factors. The analysis showed an improvement in the prediction model based purely on meteorological parameters when personal parameters were taken into account and even greater improvement when psychological factors were considered. Both linear and ordinal regression models indicated the same parameters as determinants of thermal sensation, with only two exceptions, health status and air-conditioning. In the ordinal thermo-physiological model remained the factor of health status. Overall ordinal regression results showed an improvement in relation to linear yielding better results in the case of the extreme values of thermal sensation scale. Linear showed better reproduction of TSV in the middle categories (−1, 0, +1). Regarding only

meteorological variables, thermal sensation was determined by air temperature, relative humidity, solar radiation, irradiation and ambient pressure. In the thermo-physiological model the factor of exposure time which in combination to recent experience (Place before exposure) and exposure history (Air conditioning) depicts the effect of adaptation on thermal sensation while the shading parameter highlights the importance of solar radiation. The psychological parameters that affect TSV were the season and preference that illustrate the effect of expectation and overall comfort. In the empirical model that only the objective psychological parameters were considered, the factors that showed an effect on TSV were the season and the visit purpose. People visiting the site for work tended to indicate lower thermal sensation than the predicted signifying a decisive role of adaptation in TSV. Pantavou et al. (2013) concluded that the interviewees showed better adaptation to warm than to cool environment.

The empirical model produced satisfactory results in relation to the extensive indicating that choosing the right parameters TSV could be predicted as well. According to the empirical thermo-physiological model TSV can be predicted by T_{mrt} , WS and I_{cl} .

The results of this study could be useful in estimating thermal sensation in Mediterranean climates for health and touristic purposes, as well as for planning outdoor spaces. Nevertheless this research should be expanded to greater range of weather conditions and especially in heat waves since Athens is a very popular summer destination. Moreover it would be interesting to compare the thermal sensation with the already existing models.

Appendix

The ordinal regression is used to model the relationship of an ordinal dependent variable and a set of independent variables which can be either categorical or continuous. It is an extension of generalized linear models for ordinal data (SPSS Inc, 2008). The ordinal logistic regression is a process which provides the probability of observing a particular score or less. The odds can be modeled as follows:

$$\theta_j = \frac{P(Y \leq j)}{P(Y > j)} \quad \text{or} \quad \theta_j = \frac{P(Y \leq j)}{1 - P(Y \leq j)} \tag{A1}$$

where P denotes probability, Y is the ordinal variable and j range from 1 to n-1, where n is the number of classes of the dependent variable. The category n has no odd since it covers the entire range of data and its probability is 1.

The ordinal regression model estimates the natural logarithm of the probability observing a specific value

or less. For a vector of independent variables is described by the equation:

$$\ln(\theta_j) = a_j - \sum_i \beta_i x_i \tag{A2}$$

where x_i stands for the independent variables, a_j is the threshold of the class j of the dependent variable and β_i is the regression coefficients. In the case of continuous independent variables, positive regression coefficient means that increasing the values of the continuous variable increases the possibility for larger scores and in the case of categorical variables, positive coefficient implies that the increase in the dependent variable category (e.g. category of thermal sensation vote) is more likely in the first category and negative factor that the smallest category of the dependent variable (lower score of thermal sensation vote) is more likely in the first category.

For each independent variable x is the Eq. A2 is formed as follows:

$$\ln(\theta_j) = a_j - \beta x \tag{A3}$$

Equation A3 demonstrates that in each category of dependent variable the coefficient (α) changes but the coefficient (β) remains constant. This means that the effect of the independent variable is the same for all categories of the dependent variable, and that the results can be visualized as a set of parallel lines (one line for each class). This hypothesis should be tested by allowing the calculation of the different coefficients and then checking the results on whether the rates are equal.

Solving the relation (3) for P ($Y \leq j$) the probability of getting the dependent variable a value less than or equal to class j is calculated:

$$P(Y \leq j) = \frac{e^{a_j - \beta x}}{1 + e^{a_j - \beta x}} = \frac{1}{1 + e^{-(a_j - \beta x)}} \tag{A4}$$

When there are i independent variables the Eq. A4 forms:

$$P(Y \leq j) = \frac{e^{a_j - \sum \beta_i x_i}}{1 + e^{a_j - \sum \beta_i x_i}} = \frac{1}{1 + e^{-\left(a_j - \sum \beta_i x_i\right)}} \tag{A5}$$

where β_i is the coefficient of the i independent variable. When the independent variables are categorical, the b_i and x_i are listed in each category of the categorical independent variable. So for the reference category will apply $b_i = 0$ meaning that the cumulative probability is dependent only on the corresponding α .

For each case, the predicted by the model category of the dependent variable is the category with the highest probability. In detail, on the calculation of the predicted category of the dependent variable (1) the cumulative probabilities of the dependent variable to be less or equal to each class ($P(Y \leq$

j)) is calculated by the input values (Eq. A5) (the cumulative probability of the last category n is 1) (2) the differences the probabilities of two consecutive classes ($P(Y \leq j) - P(Y \leq (j-$

1))) gives the probability of occurrence for each category (3) the class with the highest possibility is the predicted by the model category (Eq. A6) (IBM Corporation 2011).

$$\text{Predicted value} = \max \left\{ \frac{1}{1 + e^{-\left(a_j - \sum \beta_i x_i\right)}} - \frac{1}{1 + e^{-\left(a_{j-1} - \sum \beta_i x_i\right)}} \right\} \quad (\text{A6})$$

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