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Parameters that affect PMV in schools

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Abstract
It is widely accepted that the indoor environmental quality may strongly affect human's health, comfort, and productivity. This is especially true in case of school environments, as children are physically still developing and, in comparison to healthy adults, will suffer the consequences of a poor indoor environment earlier. Consequently, IEQ in schools is a very investigated topic also due to the close relationship with building energy performances. From the thermal comfort perspective, the assessment of comfort conditions is usually carried out by means of the PMV and the PPD indices. Unfortunately, the peculiarities of school environments (e.g wide classrooms, the absence of HVAC systems, the kind of activity and clothing) require high care to obtain a reliable analysis. Based on a large experience since almost 20 years by the Italian research team InEQualitES (Indoor Environmental Quality and Energy Saving), this paper is addressed to the main criticalities related to the thermal comfort assessment in schools. Particularly will be discussed the calculation of a sole PMV/PPD value to be attributed to the same classroom in the presence of more measurement positions, the effect of insulation value and, finally, how PMV index has to be used in non-air conditioned environments.

Keywords IEQ, Schools, Thermal comfort, Expectancy factor, PMV

1. Introduction

Indoor Environmental Quality (*IEQ*) as a result of the thermal, visual, acoustic comfort and the indoor air quality is a very important topic both on the energy saving point of view, as stressed by the European Community [1] and International Programs [2,3] and performances and productivity [4]. This is even more crucial in elementary school buildings because children are extra sensitive to poor *IEQ* levels with respect to healthy adults as they are physically still under development [5]. Concerning thermal comfort, the objective assessment of moderate thermal environments as schools is usually carried out by means of the *PMV* (predicted mean vote) index and the correlated *PPD* (predicted percentage of dissatisfied) [6, 7]. As recently reviewed by Forgiarini Rupp et al. [8] thermal comfort in schools has been widely investigated over the past years. Particularly, in field studies in warm climates in naturally ventilated buildings have shown that *PMV* model predicts a warmer thermal sensation than the occupants actually feel [8, 9]. This makes the assessment of the thermal comfort in schools a very complex matter, especially in those countries where *HVAC* systems are not common [10] or when the school building is protected by special laws for the safeguard of the cultural heritage (this is most common in Italy where about 20% of school building is built before 1940).

Other peculiarities concern the relationship between the predicted thermal sensation and the percentage of dissatisfied in naturally ventilated classrooms [8, 9]. Particularly, based on surveys in field, several authors revealed a certain underestimation of the percentage of dissatisfied with respect to the predicted, especially at higher or lower operative temperatures values. Finally, due to the small number of investigated subjects (it is difficult finding subjective investigations carried out on a sample made by more than 1000 students), seasonal and/or ventilation system effects, there is not a wide agreement on the thermal sensation value consistent with the minimum percentage of dissatisfied [9].

Since more than 20 years the InEQualitES (Indoor Environmental Quality and Energy Saving), group - composed by researchers and professors of the Departments of Industrial Engineering of the University of Salerno and Naples, has focused the research on the environmental quality in schools [10]. The experience gained in the field allowed us to build a large database of subjective and objective data and helped us to find effective solution aimed to solve most common problems related to the application of assessment methods [5, 11-13]

Based upon this experience, this paper is addressed to the main criticalities related to the thermal comfort assessment in schools. In particular, the calculation of a unique *PMV/PPD* value to be attributed to the same classroom in the presence of more measurement positions, the effect of insulation value and, finally, how *PMV* index has to be used in non-air conditioned school environments will be discussed.

2. Methods for the calculation of PMV/PPD mean values

As mentioned by ISO Standard 7726 [14], indoor thermal environment can be homogeneous or non-homogeneous. In the first case, only one measurement position placed at the middle is necessary, whereas for the second, several positions are required. In a typical non-homogeneous environment, like a classroom 40-50 m^2 in surface, is commonly acknowledged to identify two or three point of measurement at least, depending on the geometry, distribution of windows, terminal units, and students (see Fig. 1 as example).

According to Fanger's theory [6] the averaged *PMV* value to be attributed to the environment is the average value of *PMV* values calculated in those mentioned positions. However, it is also possible to evaluate the mean *PMV* by averaging micro-

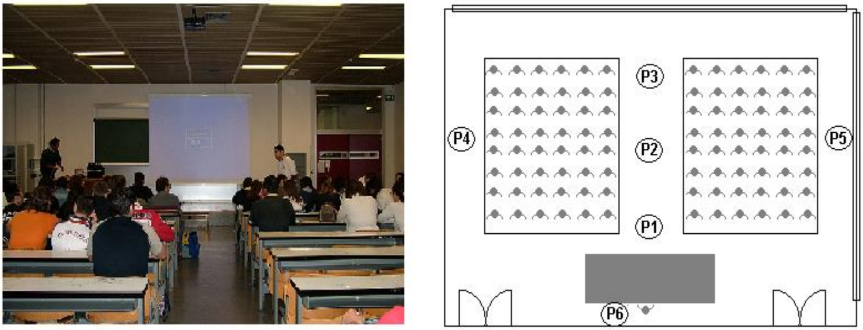

Fig. 1 Typical lecture hall where measurements have been carried out. On the right side the measurement points were depicted [15].

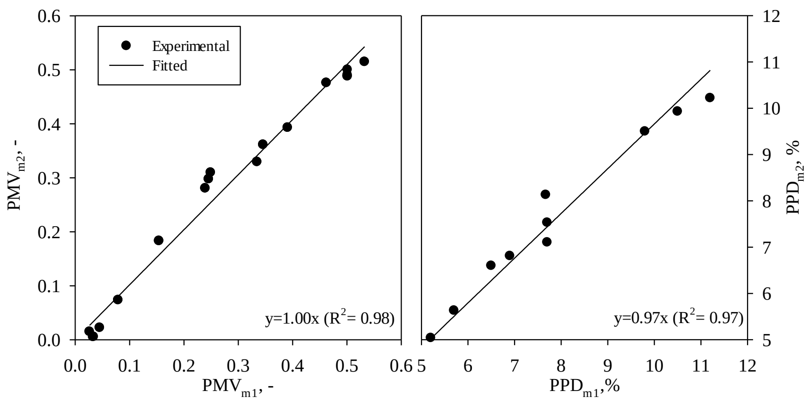

Fig 2 Comparison between *PMV_{m1} / PPD_{m1}* (obtained by averaging PMV values in each position) and *PMV_{m2} / PPD_{m2}* (obtained by averaging microclimatic variables recorded in each position) values recorded in field [15]. Metabolic rate and basic clothing insulation were settled at 1.2 met and 1.0 clo (winter), respectively.

climatic parameters measured in the different measurement positions. Unfortunately, EN ISO 7730 Standard [7] does not mention anything about this, referring to a mean value not strictly defined. Figure 2 shows values obtained by measurements performed in the monitored lecture hall in figure (1).
It is clear that, if the environment is quite homogeneous (poor differences between air temperature and mean radian temperature values) there is any difference in averaged values of votes and dissatisfied people's percentages *PPD*.

Table 1 Winter and summer season simulations: values assumed for point A. Categories for position A were attributed on the basis of EN ISO 7730 [7] and EN 15251 (between parentheses) [16].

	Winter season			**Summer season**		
	t_{rA} (°C)	**PMV_A**	**Cat.**	**t_{rA} (°C)**	**PMV_A**	**Cat.**
Case 1	12	-1.31	ND (IV)	25.5	-0.11	A (I)
Case 2	20	-0.62	C (III)	29.5	0.46	B (II)
Case 3	28	0.13	A (I)	34.5	1.21	- (IV)

To verify whether this agreement occurs also in non-homogeneous conditions, a virtual environment has been created. Particularly, two measurement points (named A and B in the text) have been considered. Position A is the "reference" point and its thermo-hygrometric parameters are fixed as follows: relative humidity RH=50%, metabolic rate M=1.2 met, air velocity v_a=0.15 m/s, air temperature for winter (summer) t_a = 20 °C (t_a = 26 °C) and basic clothing insulation for winter (summer) I_{cl} = 1.0 clo (I_{cl} = 0.5 clo). Position B exhibits the same microclimate of position A apart from the mean radiant temperature, t_r, values. In each season, three different $t_{r,A}$ values in position A have been selected (see table 1). Corresponding PMV values have been reported in table 1.

Simulations have been carried out both under typical summer and winter conditions: in winter season the mean radiant temperature in B was t_{rB}= t_{rA} ± 8 °C, while in summer season, it was t_{rB}= $t_{r,A}$ + 9 °C. In order to simulate several situations, at the beginning, thermal comfort conditions in B was considered in the same conditions of point A (PMV_A=PMV_B); then point B mean radiant temperature value was changed.

To verify the consistence of the two averaging procedures, we have calculated PMV by averaging local PMV values, PMV_{m1}, and by averaging local microclimatic values, PMV_{m2}. In Table 2, some winter simulated situations are reported for case 2. In particular, the mean radiant temperature in A is equal to 20 °C while it varies from 12 to 28 °C in position B.

According to data summarized in table 2 (in summer, similar results were obtained), the two procedures for obtaining a single PMV value for the same environment are undoubtedly consistent each other. This is true also in the presence of high asymmetries between mean radiant temperature. Unfortunately, due to the high variability of local PMV values (and related PPD) in the same environment, this occurrence does not mean a correct assessment. Therefore, at design level, the choice of large glass surfaces (or other causes of asymmetries in microclimatic parameters) needs to pay great attention to avoid unforeseeable distributions of the thermal perception in the same environment [13].

Table 2 Comparison between PMV_{m1} and PMV_{m2} for some winter situation simulated.

winter season								
	t_{rA}	**t_{rB}**	**$t_{r\,mean}$**	**PMV_A**	**PMV_B**	**PMV_{m1}**	**PMV_{m2}**
Case 2	20	12	12	-0.62	-1.32	-0.97	-0.98
		13	12.5	-0.62	-1.24	-0.93	-0.93
		14	13	-0.62	-1.15	-0.89	-0.89
		15	13.5	-0.62	-1.07	-0.85	-0.84
		16	14	-0.62	-0.98	-0.80	-0.80
		17	14.5	-0.62	-0.89	-0.76	-0.76
		18	15	-0.62	-0.8	-0.71	-0.71
		19	15.5	-0.62	-0.71	-0.67	-0.67
		20	16	-0.62	-0.62	-0.62	-0.62
		21	16.5	-0.62	-0.53	-0.58	-0.58
		22	17	-0.62	-0.44	-0.53	-0.53
		23	17.5	-0.62	-0.35	-0.49	-0.49
		24	18	-0.62	-0.26	-0.44	-0.44
		25	18.5	-0.62	-0.16	-0.39	-0.39
		26	19	-0.62	-0.07	-0.35	-0.35
		27	19.5	-0.62	0.03	-0.30	-0.30
		28	20	-0.62	0.13	-0.25	-0.26

In a similar way, at assessment level, a rough averaging of the PMV and PPD values does not appear a correct practice, especially in wide environments and in the presence of highly distributed working positions (e.g. offices and schools). In other words, the assessment of a sole PMV/PPD value is not enough to assess thermal comfort in indoor environment, but a special mapping procedure is necessary.

3. Clothing thermal insulation

Due to the high sensitivity of *PMV* index to the clothing insulation [17], this quantity has to be carefully evaluated in each experimental campaign involving schools. Therefore it is strongly recommended to assess the real I_{cl} value on the basis of the clothing ensembles that students declare to wear during the surveys. These should be indicated on special questionnaires [10] provided with a section reporting the pictures of the single garment according to ISO 9920 Standard [18]. In that way is possible to find out the mean value of thermal clothing insulation for each interviewed $I_{cl,j}$ through the following equation:

$$I_{cl,j} = \sum_{i=1}^{n} I_{clu,i} \tag{2}$$

Tab 3 Some PMV values calculated during summer investigations from standard and declared I_{cl} values. Metabolic rate M=1.2 met [19]. The labels of thermal environment quality categories were attributed according to EN ISO 7730 and EN 15251 (between parentheses).

I_{cl} = 0,5 clo		**I_{cl} by questionnaires**	
PMV	**category**	**PMV**	**category**
0,08	A (I)	0,25	B (II)
0,30	B (II)	0,43	B (II)
-0,15	A (I)	0,11	A (I)
-0,58	C (III)	-0,55	C (III)
-0,43	B (II)	-1,01	- (IV)
0,24	B (II)	0,38	B (II)
0,17	A (I)	0,54	C (III)
-0,13	A (I)	-0,52	C (III)
0,20	A (I)	0,44	B (II)

in which n is the number of the wearing clothes of the subject, $I_{clu,i}$ the effective thermal insulation of the individual i-th garment. The mean value of clothing thermal insulation for all the interviewed (m is their number) of the same classroom is calculated as:

$$I_{cl} = \frac{1}{m} \sum_{j=1}^{m} I_{cl,j} \qquad (3)$$

To stress the effect of using standard clothing insulation values (0.5 clo in summer and 1.0 clo in winter according to ISO 7730 and EN 15251 Standards), the *PMV* values and related environmental categories [7,16] are shown in Table 3 for a campaign conducted in summer condition [15].

According to data in table 3, the *PMV* values calculated using the clothing thermal insulation obtained by the subjective investigation are higher than those obtained by assuming a reference value for I_{cl}. In addition, in about 50% of cases, the environmental category shifts.

4. Naturally ventilated schools

PMV index as proposed by Fanger shows some limitations in case of naturally ventilated environment where it usually overestimates the thermal sensation felt by occupants [20, 21]. This is the reason for the increasing success of the adaptive model proposed by de Dear and Brager [22, 23] accepted by both ASHRAE [24] and ISO [7, 16]. Starting by this awareness, Fanger and Toftum [25] introduced two correction factors to extend PMV model to free-running buildings in warm climates. The first value, *e* (expectancy factor, which have to be multiplied for the PMV value to obtain the predicted thermal sensation vote), varies between 1 and 0.5 depending on the presence of *HVAC* system. For buildings provided with *HVAC* systems, the expectancy factor is equal to 1, whereas for naturally ventilated it is assumed to depend on the duration of warm climate and the possibility of compare these buildings with others in the region. The second factor introduced is a reduced activity level, as it is slowed down unconsciously by people feeling warm as a form of adaptation.

To test the expectancy approach by Fanger and Toftum and providing useful information about school environments of the Southern Italy – often built before 1940 and in several cases protected by special laws for the safeguard of the cultural heritage – over the past recent years InEQualitES team carried out a large investigation [9]. This survey (see table 4 for details) has been carried out both in summer and in winter conditions on a highest number of interviewed students (more than 4000 in the range from 11 to 18 years in more than 200 classrooms). Microclimatic surveys were combined with subjective investigation carried out by means of a specific questionnaire [23] designed in compliance with ISO 10551 Standard [26] containing five sections (personal information, thermal comfort, visual and acoustic comfort, Perceived Air Quality, *PAQ*, and global sensations).

Comparison between thermal sensation votes *TSV* obtained by questionnaires and *PMV* values from microclimatic surveys are showed in Figure 4 that demonstrates how the application of an expectancy factor equal to 0.9 results in a good agreement between predicted and subjective votes attributed to the environment in both seasons.

Tab 4 General details of investigated buildings [9].

School Name, City and year	**Number of classrooms**	**Age of the students**
Scuola Media Statale – Vietri sul Mare (Salerno), 2004	5	From 11 to 13
Scuola Media Statale "Giovanni XXIII" – Cava de' Tirreni (Salerno), 2002	11	
Liceo Scientifico Statale "A. Genoino" – Cava de' Tirreni (Salerno), 2005	26	From 14 to 18
Istituto Professionale di Stato per l'Agricoltura e l'Ambiente – Castel San Giorgio (Salerno), 2000	7	
Liceo Scientifico Statale "B. Rescigno" – Roccapiemonte (Salerno), 2003	28	
Istituto Magistrale Statale "Virgilio" – Pozzuoli (Napoli), 2006	21	
Administrated questionnaires	**Male**	**Female**
Winter	1063	1211
Summer	940	1202

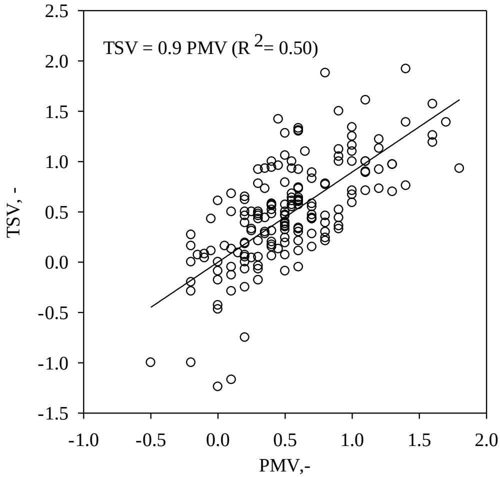

Fig 4 Comparison between the thermal sensation vote (TSV) and the predicted thermal sensation in terms of TSV and PMV indices under winter and summer conditions [8].

There are some matter to take into account:
- on the basis of both objective and subjective investigations, the microclimatic conditions observed in the different classrooms are typical of non-thermal neutrality with *PMV* > 0.
- the *PMV* index have been calculated form the real clothing insulation values of the interviewed instead of reference values (0.5 clo and 1.0 clo for summer and winter, respectively) suggested by ISO Standard 7730 (see tab 5).

Tab 5 Resultant clothing insulation $I_{cl,r}$ distribution as a function of the predicted mean vote range collected in the investigation summarized in tab 2. Each value takes into account the effect of the body movements [9, 18].

		$I_{cl,r}$, clo						
		PMV range						
		< -0.5	-0.5 ÷ -0.2	-0.2 ÷ 0	0 ÷ 0.2	0.2 ÷ 0.5	0.5 ÷0.7	> 0.7
winter	$I_{cl,max}$	-	1.4	1.44	1.44	1.49	1.4	1.4
	$I_{cl,min}$	-	1.06	1.23	1.20	1.2	1.28	1.28
	$I_{cl,mean}$	-	1.27	1.34	1.34	1.34	1.33	1.33
	SD	-	0.12	0.06	0.07	0.09	0.04	0.04
summer	$I_{cl,max}$	-	-	-	0.69	0.7	0.72	0.72
	$I_{cl,min}$	-	-	-	0.57	0.56	0.54	0.54
	$I_{cl,mean}$	-	-	-	0.63	0.63	0.63	0.63
	SD	-	-	-	0.04	0.04	0.04	0.04

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Tab 6 Expectancy factor values proposed by Fanger and Toftum [25] for non-air conditioned buildings in warm climates. NV = Natural Ventilated; AC = Air Conditioned.

Expectation	**Classification of building**	**Expectancy factor, e**
High	NV buildings located in regions where AC buildings are common. Warm periods occurring briefly during the summer season.	0.9–1.0
Moderate	NV buildings located in regions with some AC buildings. Warm summer season.	0.7–0.9
Low	NV buildings located in regions with few AC building.	0.5–0.7

- the choice of using real clothing thermal insulation values is due to the low correlation between the *TSV* observed values and *PMV* values calculated by means of reference summer and winter clothing insulation values which were about 20 - 25% lower for the investigated sample of students

The application of an expectancy factor equal to 0.9 results in a good agreement between predicted and subjective votes attributed to the environment in both seasons. This is consistent with Fanger and Toftum's findings who proposed a value in the range 0.9 e 1.0 (see tab 6) for naturally ventilated buildings placed in climatic areas with short warm period (this the climate here investigated) during the summer and it is also surprising as it takes into account both summer and winter data.

5. Conclusions

This short paper, based on a large experience in the field, has stressed how many aspects of the objective evaluation of thermal comfort in schools by means of the *PMV*/*PPD* indices are still unclear or require paying great attention. In particular, according to our findings we can conclude that Fanger's basic approach for the assessment of the thermal comfort is effective also in naturally ventilated schools if a right expectancy factor and the real clothing insulation worn by students are known. Finally, form the measurement point of view, our experience has demonstrated as the availability of special protocols is a crucial element for a reliable evaluation. This is especially true in wide environments (e.g. offices) and in the presence of highly distributed working positions or phenomena responsible for heterogeneities in microclimatic parameters.

References

[1] European Union. Directive 2012/2 7/EU of The European Parliament and of the Council of 25 October 2012 on energy efficiency amending Directives 2009/125/EC and2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC. Official Journal of the European Union n. L 315/1 of the 14.11.2012.
[2] http://ec.europa.eu/programmes/horizon2020/en/what-horizon-2020 (accessed 01.31.16).
[3] http://www.renew-school.eu/en/home/ (accessed 01.31.16).
[4] Andersson J. Boerstra A. Clements-Croome D. Fitzner K. Hanssen SO. Indoor climates and productivity in offices. In: Wargocki P. Seppänen O. editors. REHVA guidebook 2006 (6).

[5] Bellia L. Boerstra A. van Dijken F. Ianniello E. Lopardo G. Minichiello F. et al. Indoor environment and energy efficiency in schools e part 1. principles. In: d'Ambrosio Alfano FR. editor. REHVA guidebook 2010 (13).
[6] Fanger PO. Thermal Comfort: Analysis and Applications in EnvironmentalEngineering. Danish Technical Press. Copenhagen. 1970.
[7] CEN. 2005. Ergonomics of the thermal environment - Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. Standard EN ISO 7730. Bruxelles: Comité Européen de Normalisation.
[8] Forgiarini Rupp R. Giraldo Vásquez N. Lamberts R. A review of human thermal comfort in the built environment. Energy and Buildings 105 (2015) 178–205.
[9] d'Ambrosio Alfano FR. Ianniello E. Palella BI. PMV–PPD and acceptability in naturally ventilated schools. Build. Environ. 67 (2013) 129–137.
[10] Zhang G. Zheng C. Yang W. Zhang Q. Moschandreas DJ. Thermal comfort investigation of naturally ventilated classrooms in a subtropical region. Indoor Built Environ. 16 (2007) 148–158.
[11] Errigo M., Liotti F., Mol, R., Palladino S., Labella A., Alfano G., Betta V., Cesarano A., d'Ambrosio F.R. Indagine ergonomica in ambiente scolastico. Proceedings of the IV National Congress of the Ergonomics Italian Society (SIE) Ischia, May 1988, CUEN 179-188 (In Italian).
[12] d'Ambrosio Alfano FR, Ianniello E, Ziviello C. A protocol for objective and subjective assessment of global comfort in school environments. In: 10th International conference on air distribution in rooms, Roomvent, Helsinki, 2007 June 13the15th, vol. 1. p. 142-146.
[13] d'Ambrosio Alfano FR. Olesen BW. Palella BI, Riccio G. Thermal Comfort: Design and Assessment for Energy Saving. Energy and Buildings 81 (2014) 326–336.
[14] ISO 7726. Ergonomics of the thermal environment – instruments for measuring physical quantities. Geneva: International Standardization Organization; 1998.
[15] d'Ambrosio Alfano FR. Ianniello E. Riccio G. Notes on the evaluation of global comfort by PMV e PPD indices. Proceedings of Climamed 2007 Conference.
[16] EN 15251. Criteria for the Indoor Environment including thermal. indoor air quality. light and noise. Bruxelles: Comité Européen de Normalisation; 2007.
[17] d'Ambrosio Alfano FR, Palella BI, Riccio G. The role of measurement accuracy on the thermal environment assessment by means of PMV index. Build Environ 2011; 46(7):1361-1369.
[18] ISO 9920. Ergonomics of the thermal environment e estimation of the thermal insulation and evaporative resistance of a clothing ensemble. Geneva: International Standardization Organization; 2009.
[19] ISO 8996. Ergonomics of the thermal environment e determination of metabolic rate. Geneva: International Standardization Organization; 2004.
[20] Fanger PO. Toftum J. Extension of the PMV model to non-air-conditioned buildings in warm climates. Energ Buildings 2002; 34: 533-536.
[21] van Hoof J. Forty years of Fanger's model of thermal comfort: comfort for all? Indoor Air 2008;18:182-201.
[22] Brager GS, de Dear RJ. Thermal adaptation in the built environment: a literature review. Energ Buildings 1998; 27(1): 83-96.
[23] Brager GS, de Dear RJ. A standard for natural ventilation. ASHRAE J 2000; 42(10): 21-28.
[24] ASHRAE 55. Thermal environmental conditions for human occupancy. ANSI/ASHRAE Standard 55. Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc; 2013.
[25] Fanger PO, Toftum J. Extension of the PMV model to non-air-conditioned buildings in warm climates, Energy and Buildings 34 (2002) 533–536.
[26] ISO 10551. Ergonomics of the thermal environment e assessment of the influence of the thermal environment using subjective judgement scales. Geneva: International Standardization Organization; 1995.