The adaptive approach to thermal comfort: from models to solutions

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ABSTRACT
A series of thermal comfort field data (about 1800 observations), collected in Bari (Southern Italy), were implemented according to the ASHRAE RP-884 world database format, thus constituting a local database for the Mediterranean area, which, with exception of Greece, is not represented in this world database. The collected data, mostly already published, were re-examined in the light of the latest international literature on the subject.

Within the adaptive modelling of thermal comfort, to which this survey can be related, the behavioural factors of individual type, like clothing thermal insulation and level of activity do not appear explicitly, although their basic role played in the interaction man–environment is recognized. Therefore these factors were analysed.

Furthermore, an analysis was conducted on thermal sensation, thermal preference and dissatisfaction indices and an adaptive control algorithm was developed.

In the conclusion it is argued that research in this field, however, is moving beyond the narrow limits of thermal, even though adaptive, comfort zones, to which previous studies have so far led us.

INDEX TERMS
Thermal Comfort, Human Response, Adaptation.

INTRODUCTION
This contribution can be framed within the adaptive approach to pursue solutions of thermally comfortable buildings. Among the main useful outcomes of this approach that must be mentioned are: (i) the thermal comfort model derived from the ASHRAE RP884 Project (de Dear and Brager, 1998) aimed at revising the current International Standards on building and services design; (ii) the adaptive control algorithm derived from the European SCATs Project (McCartney and Nicol, 2001) aimed at building management systems design. The extensive studies underlying these research results were assumed as reference, here, for a comparison with a local data bank built on the basis of field thermal surveys carried out in Bari (41°08′N, 16°47′E). The collected data, most of which have already been published (Conte and Fato, 1997, 1998, 2000), were re-examined with the aim of validating this data bank and continuing research on the characterization of human response to thermal environment, an essential aspect for intelligent climate control systems design. The data bank is made up of four measurements surveys, two in the winter and two in the summer seasons, involving university buildings and a rather young student population of healthy, motivated subjects. Table 1 refers to the summary of some mean quantities, describing the individual characteristics of the interviewed subjects and the measured environmental conditions, for each survey.

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Table 1 Summary of mean measured quantities, for season and year

Field survey	S95	W96	S99	W00
N_q	423	1034	250	131
N_m	31	50	31	17
N_g	6	8	3	4
T_{ext} (°C)	21.74	9.23	28.23	11.56
T_{rm} (°C)	20.60	8.81	25.97	10.73
Top (°C)	27.54	19.46	27.93	23.46
Insul (clo)	0.54	0.99	0.55	0.97
Ash	0.85	–0.43	1.0	0.62

METHODS

The research was developed on the basis of environmental and comfort data surveyed in the period 1995–2000 during different seasons and thermal regimes in university rooms, mostly libraries. The survey was of transverse type and the measurement protocol followed ISO Standards 7726 and 10551. The thermal modes were: free running in summer 1995 (S95), controlled mode (heated) in winter 1996 (W96), controlled mode (air conditioned) in summer 1999 (S99) and winter 2000 (W00). A general description of the local climate, surveyed buildings and services was reported in a previous contribution (Conte and Fato, 2000) to which the last survey (W00) has to be added. All data have been only recently introduced into a spreadsheet in the format of the world data bank of the ASHRAE RP-884 Project, and for reasons of uniformity, the PMVs were re-calculated making use of the routine of Fountain and Huizenga (http://atmos.es.mq.edu.au/~rdedear/pmv/). The local data bank was elaborated for highlighting the dependence of the responses on the external climate, personal thermal experience, population characteristics and type of internal microclimatic control. In pursuing such correlations, the data (N_q represents number of questionnaires in Table 1) were grouped for measurement point (N_m represents number of measurements) and then for one-degree temperature intervals (N_g represents number of temperature intervals), weighing the elaborated variables, the weights being given by the number of subjective responses of the measurements included in each interval. In the correlations where the mean/running external temperature was assumed as independent variable, the grouping of responses was made on a daily basis.

Within the adaptive modelling of thermal comfort, to which this survey can be related, the behavioural factors of individual type, like clothing thermal insulation and level of activity do not appear explicitly, although their basic role played in the interaction man-environment is recognized. Therefore these factors were analysed by: (i) evaluating the influence of both thermal indoor and outdoor conditions on clothing insulation; (ii) comparing the metabolic rate values indirectly derived from the actual thermal sensation votes of the occupants and the corresponding values estimated on the basis of anthropometric characteristics as well as the corresponding standardized values. Furthermore, a regression analysis was conducted for thermal sensation, thermal preference and dissatisfaction indices.

Within the climatic context of this survey, the outcomes of the European SCATs Project (1997–2000) on the development of an adaptive control algorithm were assumed as reference for a similar processing of available data.

RESULTS AND DISCUSSION

Table 2 shows the parameters of the statistical regression of INSUL versus the room operative temperature, for each season surveyed and, in the last two columns, for the RP884 air-conditioned (AC) and natural ventilated (NV) buildings. The gradients show an expected, inverse relation for all surveys, except for Summer 1995 for which the clothing adaptation of occupants would seem independent from indoor thermal conditions that were of a free-running mode building. In the following rows of the table the same data were correlated with the outdoor mean temperature and here an opposite gradient can be observed for the two buildings modes in which surveys can be grouped, NV for S95, W96 and AC for S99, W00. On average, regression gradients are lower than the corresponding RP884 for each control mode. These results highlight dependency of clothing insulation on internal expected conditions for controlled mode and on external experienced conditions for natural ventilated, particularly free-running, buildings.

Table 2 Parameters of regressions INSUL-TOP, INSUL-$T_{m\text{-}ext}$

Field survey/ Type of building	S95	W96	S99	W00	AC	NV
INSUL-TOP						
Intercept	0.42	1.43	1.21	2.12	1.73	2.08
Gradient	0.005	–0.02	–0.02	–0.05	–0.04	–0.05
r^2	0.22	0.73	0.91	0.66	0.18	0.66
INSUL-$T_{m\text{-}ext}$						
Intercept/costant	0.96	0.97	0.14	0.67	0.93*	2.08
Gradient/exponent	–0.02	–0.005	0.01	0.03	–0.01*	–0.05
r^2	0.88	0.00	0.51	0.98	0.64*	0.44

*Data referred to an exponential regression.

Metabolic rate values, of different and independent derivations, were then compared for testing the assumption of standard values, independent of personal characteristics. Table 3 reports a series of values of metabolism (met) that were estimated or calculated, for each survey, with: (i) $M_{ISO7730}$, value estimated from the corresponding ISO standard on the basis of activity type; (ii) $M_{ISO8996}$, analogously, value estimated on the basis of a more accurate analysis of the activity and from the percentage of male and female respondents; (iii) M_P, value predicted from the equation of Xavier and Lamberts (1998) in function of individual age and weight; (iv) M_{PMV}, value indirectly derived from PMV equation putting PMV equal to ASH.

Table 3 Summary of mean estimated or calculated values of metabolism

	S95	W96	S99	W00
$M_{ISO7730}$	1.2	1.2	1.2	1.2
$M_{ISO8996}$	1.16	1.17	1.17	1.17
M_P	1.09	1.09	1.09	1.08
M_{PMV}	1.5	1.4	1.2	1.7

Assuming $M_{ISO7730}$ as reference value, the other series and the relative discrepancies can be explained: (i) the lower $M_{ISO8996}$ values by the presence of a lower percentage of females in the groups of respondents; (ii) the even lower M_P values by the average young age in conjunction with the registered percentage of females; (iii) by M_{PMV} being assumed as a measure of the applicability of PMV model in field. Comparing the last row, therefore, with the $M_{ISO7730}$ constant value of 1.2 met, it can be said the PMV model is appropriate in conditioned rooms like the S99 ones, less appropriate in controlled, only heated, rooms as in W96 and even less again in free-running rooms, as in S95. For W00 with air conditioned rooms, the unexpected discrepancy cannot be explained by a higher activity level of the occupants, but rather by the anomaly of the indoor operative temperature of 23.46°C in this surveyed building and by a shift from neutral to preferred judgement of the occupants.

Subjective responses and environmental parameters of the local data bank allow correlation of actual thermal sensation (ASH), predicted thermal sensation (PMV) and actual thermal preference votes (MCI) with the indoor temperature. Figure 1 shows the tendency lines of ASH, PMV, MCI versus TOP, as a result of merging all data. ASH and PMV are expressed on a seven-point scale, MCI on a three-point scale, with 3 for warmer, 2 for no change, 1 for cooler. The lines reveal good consistency in replies, but a lower slope for the preference line rather than the thermal sensation line and a little shift in preferred temperature compared to neutral temperature.

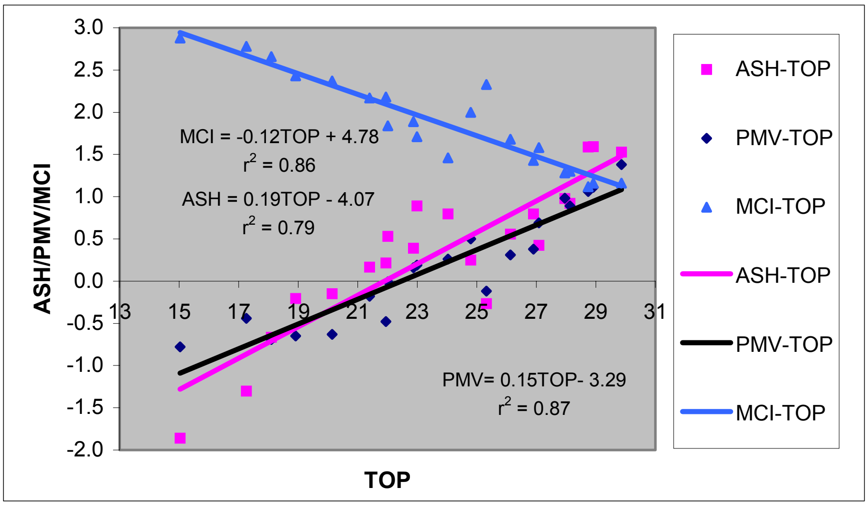

Figure 1 Correlations PMV-TOP, ASH-TOP, MCI-TOP.

Actual thermal sensation votes were also analysed from the point of view of the actual percentage of dissatisfied people (PD), as compared: (i) with the predicted percentage of dissatisfied (PPD) of the PMV model and (ii) with the exponential adjustment found by Xavier and Lamberts in a field survey carried out in Brazil.

Figure 2 shows good agreement between field curves of PD and a substantial coincidence of 34% as percentage of dissatisfied for PMV = ±0.5. If this result of PD = 34% for thermoneutrality interval limits were confirmed still further, a psychological effect could be hypothesized, for which 66% people normally agree with the actual prevailing life situations and conditions, thermal or not thermal.

Local dependence of comfort temperatures on weather conditions was investigated too. Within the climatic context of this survey, the outcomes of the European SCATs Project on the development of an adaptive control algorithm (ACA) for building management systems design were assumed as reference for a similar processing of local data. In the SCATs project, to which UK, France, Sweden, Greece and Portugal have contributed, the running mean outside temperature was correlated to comfort temperature, calculated by means of an equation, from thermal sensation votes.

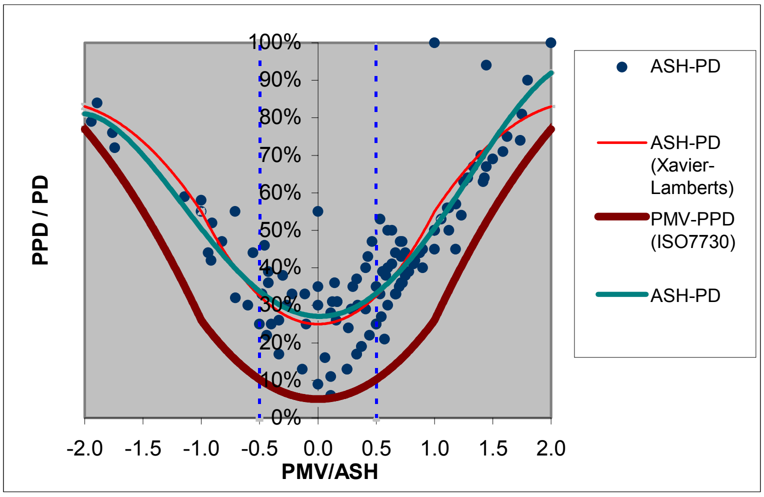

Figure 2 Correlations between predicted/actual thermal sensation and predicted/actual percentage of dissatisfied people.

In search of an ACA for Southern Italy, two correlations were built from both thermal sensation votes and thermal preference votes. The comfort temperatures were predicted by regression analysis and the running mean outside temperature was calculated as TR80. The outcomes together with the ACA for the SCATs project, are shown in Figure 3 where (i) the line of T_c for Italian ACA has a higher slope than SCATs for all the countries, even though very close to the individual ACA for Portugal (gradient = 0.38); (ii) the preference of people for warmer rather than neutral temperatures in the cold season and the opposite in the warm season is confirmed (de Dear and Brager, 1998), the inversion point being around T_{rm} = 18°C, characterizing the intermediate seasons.

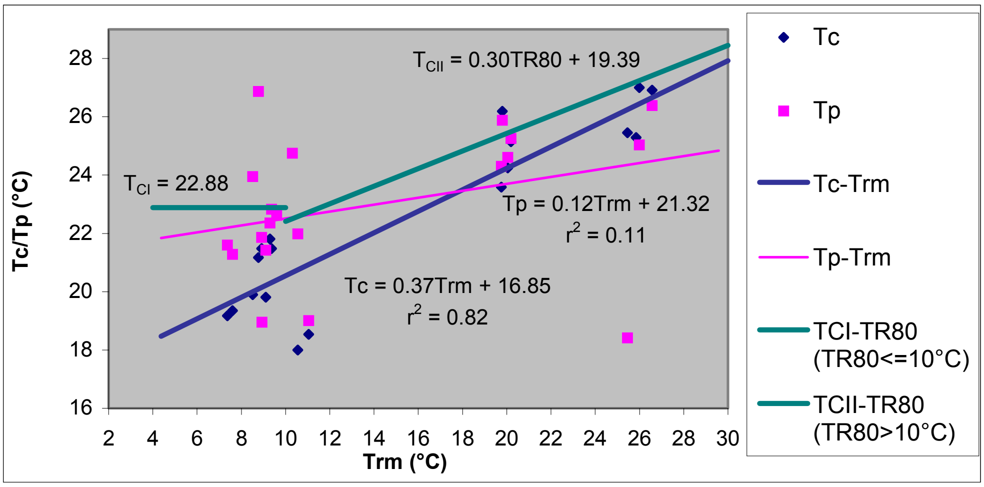

Figure 3 Adaptive control algorithms for Southern Italy and for European SCATs countries.

CONCLUSION AND IMPLICATIONS

The analysis of the local data bank for Bari (Southern Italy) aimed mainly at validating the collected data, through a comparison with similar studies, and at continuing research on the characterization of human response to indoor thermal environment.

But looking at European research, particularly at EU FP6 as expressions of interest shown in its preliminary stage, a new approach to thermal comfort seems to be going beyond a mere revision of a static, even though adaptive, comfort model, which includes all people's comfort needs. In today's multiethnic society, in the era of easy moving across continents, in a world where preferences are emphasized more than primary needs, where expectations and habits are often conditioned by the media, as in the case of fashion, the concept and subsequent use of a standardized and limited thermal comfort zone, seem decidedly obsolete. European research is today oriented towards adaptive buildings, with proposals mostly of two kinds. Researchers of architectural education emphasizing energy savings, propose buildings fitted to external climate, whereas researchers of electronic education, emphasizing actual human needs, propose intelligent climate control systems. The two approaches should be integrated, however, the most innovative to comfortable buildings design is the second.

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