Comparison between thermal comfort predictive models and subjective responses in Italian university classrooms

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SUMMARY

This work is focused on the evaluation of indoor thermal quality and shows some results of a wider field study in university classrooms. The field study was conducted through physical observations and questionnaires, performed at the same time during the regular lesson time, in a period just before the start of the heating season. The predictions of dissatisfied occupants, based both on Fanger’s heat balance model and on an adaptive approach, were compared to each other. The subjective survey investigated the thermal acceptability, the thermal preference and the thermal sensation, asking students to assess their comfort on subjective scales. The calculated predicted votes were compared to the observed subjective responses. Moreover, the subjective mean votes were compared to the thermal environment perceptions in terms of acceptability and preference. The obtained results give a contribution to the enrichment of knowledge about thermal subjective responses in classrooms.

INTRODUCTION

Recently, CEN is working at the assessment of indoor environmental quality criteria, with the formulation of the prEN15251 European Standard Project [1]. The prEN15251 is strictly related to the European Directive 2002/91/EC [2], about energy efficiency of buildings, and deals with energy consumption problems; it proposes a method for the classification and certification of indoor environmental quality (IEQ), under the point of view of thermal comfort, visual comfort, acoustic comfort, indoor air quality and global comfort [3]. The IEQ affects not only health and comfort, but also the occupants’ productivity, so it strongly influences the general quality of working and educational environments, having repercussions on production costs and social costs. In particular, schools are a category of buildings in which a high level of environmental quality may considerably improve occupants’ attention, concentration, learning, hearing and performances [4].

This study is focused on thermal comfort and aims at achieving a better knowledge about the subjective perception in naturally ventilated environments, in which the occupants have only some opportunities of behavioural adjustment. A particular, but significant, case is here analysed: naturally ventilated university classrooms. The comparison between the subjective votes and the predicted votes, deriving from the objective monitoring of thermal parameters, allows the test in field of different existing criteria, based both on a deterministic approach and on an adaptive approach.

This study is part of a wider research started by the Building Physics and Indoor Environment Engineering Research Group (see http://www.polito.it/ftarch) of the Department of Energy (DENER) of the Politecnico di Torino, which was focused on environmental comfort in Italian school buildings [5,6]. This paper focuses on the results from the thermal comfort field.
investigations in university classrooms. The field campaigns were performed during the lesson periods.

At present, two different approaches to the definition of thermal comfort coexist, each one with its potentialities and limits: the former is deterministic, the latter is adaptive. Fanger’s model [7] based on steady state heat transfer theory, has a deterministic approach and provides the basis of the main thermal comfort standards [8,9], for mechanically controlled environments.

Adaptive comfort models derive from field studies, having the purpose of analysing the real acceptability of thermal environment, which strongly depends on the context, on the behaviour of occupants and on their expectations. The analysis of “real-world” settings reveals that thermal preferences depend on the way people interact with their environment, modifying their own behaviour and adapting their expectations, to match the thermal environment [10].

Moreover, the recent studies on adaptive comfort approach qualify the thermal comfort not only by asking a judgment about the thermal sensation, but also by investigating the acceptability and preference of the indoor thermal condition with respect to conditions corresponding to thermal neutrality [11,12]. This tendency of preferring certain thermal environments was already argued by McIntryre [13]. In his studies, he found out that people of warm climates may prefer what they call a “slightly cool” environment and, on the contrary, people of cold climates may prefer what they call a “slightly warm” environment. Furthermore recent field studies in classrooms confirm that people in naturally ventilated indoor environment are comfortable within a range of microclimate values that is larger than in a fully conditioned indoor environment [14].

Among the adaptive comfort diagrams, this study referred to the one developed in a recent EU-funded research project coordinated by the Oxford Brookes University (figure 1) [15]. This diagram is adopted into Standard prEN15251/2006 [1].

![Figure 1. Adaptive thermal comfort diagram for the design of naturally ventilated environments, adopted into Standard prEN15251/2006](image)

**METHODS**

**Object of the study**

In this study, a methodology based on both objective and subjective surveys for in field evaluation of thermal comfort was applied. The approach consists of administrating a
questionnaire to a group of occupants while the investigator records certain microclimatic parameters [6,11,14].

Such an investigation methodology is very important in classrooms, that are an example of indoor environment in which the adaptive opportunities are quite limited during the lessons period, but they are free during the hourly lesson breaks. In fact, students have to spend lots of time in listening and understanding lessons, remaining sitting at their desk. Moreover, the freedom of students in modifying and adjusting their activity level according to the thermal environment is, to a certain extent, limited during the lesson time, as well as the possibility to change the functioning parameters of the HVAC systems or to open/close the windows. But the same actions are free during the lessons breaks. The adaptive actions of the students to modify the microclimate parameters may include adding or removing layer of clothing, opening or closing windows, moving sun shading devices, etc. [10].

A previous study examined a representative sample of typical high school and university Italian classrooms; the study was performed during the heating period, that in Turin ranges from 15th October to 15th April; in particular, the investigations were carried out from the end of January to April 2002. The results are shown in [6].

The object of this study, an extension of the previous study, is a university classroom of the Politecnico di Torino, medium-sized and parallelepiped-shaped. The classroom is located at ‘‘Via Boggio’’ campus, a new building in a residential area at the border of Turin downtown, next to the headquarter of the Politecnico di Torino. The classroom has a floor area of 142 m², a height of 3,4 m and a volume of 483 m³; the ratio of glassed area/floor area is W/F = 0,15; the exposition is E–SE. The classroom was examined during the lesson time, in two periods, the first in September and the second in October 2006, outside the heating season, with outdoor warm or mild climate conditions; the direct solar radiation into the classroom was important during the first survey, while the sky was cloudy during the second. Heating through radiators and mechanical ventilation were off during the field campaigns. The classroom contained 103 students at the time of the first survey and 108 in the second.

Two different comfort criteria, Fanger’s PMV [7], and the adaptive thermal comfort diagram (figure 1) [15], were applied to a naturally ventilated university classroom and the results were compared with the subjective votes of the students. Furthermore the votes of thermal preference were compared to the votes of thermal sensation.

Subjective approach

The subjective approach was basically aimed at finding out the judgement about the perception of the thermal environment in terms of acceptability and preference of colder or warmer environments. Moreover, a vote on the Fanger’s 7-points thermal sensation scale was asked to students.

Questionnaires were used to investigate the thermal perception. They were delivered and filled by the students while the measurements (see Section 3.3) were going on. The answers to the questions concerned the instantaneous assessment of microclimatic conditions. Students were uniformly distributed in their own classroom during their regular lecture hours. The questionnaire was specifically set-up for the assessment of thermal quality in classrooms. It is a section of a more complete questionnaire, concerning the general environmental quality in classrooms, developed by an équipe of indoor environment engineers, mathematicians and physiologists. Its final shape belongs to the results of a number of tests aimed at verifying the reliability of the way in which the questions are proposed and the answers are done.

With regard to thermal comfort, among the general information, it was asked to the students to mark what they were wearing by means of a clothing check-list, in order to find out the actual clothing level (calculated using ISO 7730 [16]). This information was used in the evaluation of the PMV comfort index.
The questions in the section of thermal comfort concerned how the thermal environment was felt. In particular, students gave a judgement about its acceptability and preference, answering the following questions [6,11,14]:

- at this moment, do you consider the thermal environment acceptable or not?
- at this moment, would you prefer to feel warmer, cooler or no change?

Moreover, a judgement on the typical seven points thermal sensation scale (Fanger 7-points scale, ranging from -3 to +3, corresponding to very cold and very hot and 0 being the thermal neutral condition) was asked [7].

**Objective approach**
The indoor thermal environment was analysed by means of field measurement campaigns. The measured thermal parameters were:

- air temperature,
- plan radiant temperatures,
- air relative humidity,
- mean air velocity and standard deviation of air velocity.

The Indoor Climatic Analyser, type 1213 by Brüel&Kjær was used to perform the measurements of all the thermal parameters and 6 microdataloggers type 175-T1 by Testo, to measure air temperature. The measurements took at least 2 hours and were done only during the lesson time.

The parameters were measured in continuous at a height of 1.1m above the floor, according to the standard ISO 7726:1998 [16] for seated persons, for the whole classroom.

On the basis of ISO 7730 [9], two forms of local thermal discomfort were verified: from the mean air velocity and standard deviation of air velocity, the draft risk was evaluated and the local discomfort from radiant asymmetry was evaluated.

As far as the personal parameters are concerned, the metabolic rate was fixed at 1.2 met (sedentary activity) and the actual people clothing were obtained from the questionnaires.

The recorded data were elaborated in order to evaluate the thermal comfort Fanger’s indices, PMV and PPD, according to ISO 7730 [9]; the clothing levels and the values of the thermal parameters were quite homogeneous, so the PMV was calculated from the medium values of the parameters.

In order to apply the adaptive diagram of figure 1, the “outdoor running mean temperature” was calculated from the outdoor daily mean temperatures of the days preceding the examined one (day n), with this formula [1,15]:

\[ t_{ORM(n)} = (1 - \alpha) \left( t_{OMD(n-1)} + \alpha t_{OMD(n-2)} + \alpha^2 t_{OMD(n-3)} + \ldots \right), \]

where \( t_{ORM(n)} \) is the running mean temperature in the day \( n \), \( t_{OMD(n)} \) is the outdoor daily mean temperature in the day \( n \) and \( \alpha \) is a constant between 0 and 1, defining the speed at which the running mean temperature responds to the outdoor temperature (a value of 0.8 implies that the characteristic time subjects take to fully adjust to a change in the outdoor temperature is around 5 days and corresponds to the highest correlation with comfort sensation).

The outdoor daily mean temperatures of the days preceding the examined one were obtained from hourly data, measured by the Meteorological Station of the Politecnico di Torino; the resulting values of the “outdoor running mean temperature” for the two examined days were respectively 19,8 °C and 20,1°C.

So the indoor operative temperature ranges were obtained from the adaptive thermal comfort diagram of figure 1, in function of the values of outdoor running mean temperatures previously found. The diagram of figure 1 shows three tolerance ranges for the indoor
operative temperature, corresponding to three different expected percentages of satisfied people (90%, 80% and 65%).

RESULTS

As explained in the previous paragraph, the whole classroom was qualified “objectively”, that is on the basis of measurements, observations and calculations, both through a deterministic and an adaptive approach, obtaining the following results for the global thermal comfort:

- a value of PMV and PPD for the whole classroom, according to the deterministic approach;
- an expected value of dissatisfied occupants, deriving from the comparison between the range of values assumed by the indoor operative temperature and the tolerance ranges obtained from the adaptive diagram for the examined day.

First of all, these two results were compared to each other, then these results were compared to the subjective votes deriving from the questionnaires.

As far as local thermal discomfort is concerned, two forms of local thermal discomfort (draft risk and radiant asymmetry) were evaluated, as explained in the previous paragraph. Both these evaluations didn’t show any critical situation under the point of view of local discomfort, in both the surveys.

For both the examined days, the obtained value of PPD was < 10% (9% and 8% respectively). Considering that no particular forms of local thermal discomfort existed, in both the examined days, the expected percentage of satisfied was less than 10%.

Comparing the indoor operative temperatures to the tolerance ranges, with the adaptive approach, the expected percentage of satisfied people was at least 90% (indicated as PPD_adapt < 10%); in this case the use of the diagram would predict the effect of both global and local thermal comfort.

So the two “objective” approaches lead approximately to the same results, in predicting the percentage of dissatisfied. The coincidence of the two approaches might depend on the fact that, in the examined period, the outdoor climate is not extreme.

The expected percentage of dissatisfied (< 10%) was compared to the percentage of dissatisfied from the questionnaires, calculated as follows.

The dissatisfied people were first evaluated through the direct votes “non acceptable” expressed by the students for the thermal environment: this percentage is indicated as PD_direct in table 1.

A second way of evaluating the dissatisfied people was considering the ones voting (-3;-2) and (+2;+3) on the seven points thermal sensation scale, following the same approach used by Fanger in its experiments; this percentage was slightly corrected adding to it the percentage of students voting (-1,0,+1) but expressing discomfort for draft (indicated as PD in table 1). Then, with a third approach, the dissatisfied people were considered the ones voting (-3;-2) and (+3) on the seven points thermal sensation scale; also in this case, this percentage was slightly corrected adding to it the percentage of students voting (-1,0,+1,+2) but expressing discomfort for draft (indicated as PD* in table 1).

<table>
<thead>
<tr>
<th>Survey</th>
<th>PPD</th>
<th>PPD_adapt</th>
<th>PD_direct</th>
<th>PD</th>
<th>PD*</th>
</tr>
</thead>
<tbody>
<tr>
<td>September</td>
<td>9%</td>
<td>&lt; 10%</td>
<td>24%</td>
<td>20%</td>
<td>6%</td>
</tr>
<tr>
<td>October</td>
<td>8%</td>
<td>&lt; 10%</td>
<td>29%</td>
<td>24%</td>
<td>9%</td>
</tr>
</tbody>
</table>
The results presented in Table 1 show that both PD_direct and PD, resulting from questionnaires are always sensibly higher than the calculated PPD and PPD_dapt. In particular, vote +2 (hot) is considered unacceptable by the Fanger approach. On the contrary, in the preformed study, environments voted as +2 seem to be partially accepted, as it is pointed out through the analysis of the subjective judges about ‘‘acceptability’’ and ‘‘preference’’ of a thermal environment. In fact, considering as dissatisfied people voting (-3; -2) and (+3) and as satisfied people voting (+2), the PD* agrees well with the measured PPD. This issue was also argued by Mayer [12]. A similar result emerged from the previous study [6], which was conducted only during the heating season, but it is important to note that in that period this trend was more evident, in fact environments voted as +2 seemed to be more accepted and also preferred.

The judgments on the seven points thermal sensation scale were then correlated to acceptability and preference, as shown in Figs. 2, 3 and 4.

![Figure 2](https://via.placeholder.com/150)

**Figure 2.** Frequency distribution of thermal acceptability votes versus thermal sensation votes

![Figure 3](https://via.placeholder.com/150)

**Figure 3.** Frequency distribution of thermal preference votes versus thermal sensation votes

In particular, in Fig. 2 the frequency distribution of the acceptability is presented versus the subjective vote about the thermal environment. Both the results of the surveys show that the distribution of ‘‘acceptable’’ is shifted toward the positive side of the vote scale; in particular, most of the people voting +1 considered ‘‘acceptable’’ the thermal environment. It is important to note that in the previous winter
study a similar trend was found for the examined classrooms, but with a more accentuated acceptability of warmer environments.

These statements are also verified by the diagrams in Fig. 3, plotting the frequency distribution of the preference versus the subjective vote about the thermal environment. A very high percentage of votes “no change” corresponds to the vote +1, in particular for the second survey. The same phenomenon was very remarkable in the previous winter surveys. Plotting the cumulative frequency distribution of “wanting warmer” and “wanting colder” versus the subjective judgment on thermal environment (Fig. 4), show the location of the point corresponding to the minimum number of dissatisfied. This point is at the intersection between the two cumulative curves. The figures show that such minimum does not coincide with the thermal neutral condition (0 in the subjective vote) but is slightly shifted toward the positive values of the vote scale.

Figure 4.

DISCUSSION

In this work, a in field investigation methodology on thermal comfort was applied. The environmental parameters influencing thermal comfort were measured while, at the same time, the subjective judgements of the people about the thermal environment were expressed. Significant tendency and correlation were found out. The investigations were performed in the same university classroom in two different days, in September and October, before the beginning of the heating period.

This study allowed a comparison between different predictive approaches for thermal comfort and a comparison between the predictions and the observed subjective responses. Furthermore it added new findings to previous researches conducted in Italian university and high school classrooms, during the heating season. The results of this study confirmed the trend outlined by the previous study, but with a minor intensity, suggesting a correlation between the thermal acceptability and preference and the outdoor temperature.

The following results were found:

• it was found out a bad agreement between the calculated PPD and the percentage of dissatisfied from the questionnaires when people voting (-3; -2) and (+2; +3) on the seven points thermal sensation scale are considered all dissatisfied;
• it was found out a good agreement between the calculated PPD and the percentage of dissatisfied from the questionnaires when people voting (+2) on the seven points thermal sensation scale are considered satisfied.
• thermal environments which are judged neutral or slightly warm are accepted;
• thermal environments which are judged slightly warm might be preferred;
• in thermal environments which are judged as slightly cold, ‘‘wanting warmer’’ people are a high percentage and might prevail;
• in thermal environments which are judged as neutral, ‘‘no change’’ people prevail and there are no votes of ‘‘wanting warmer’’;
• in thermal environments which are judged as slightly warm, ‘‘no change’’ people are a high percentage and might prevail.

REFERENCES