PRACTICAL APPLICATION OF A NEW METHOD FOR THE ASSESSMENT OF COMFORT, HEALTH AND PRODUCTIVITY IN OFFICES

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ABSTRACT

In present-day society, people spend 90% of their time in enclosed spaces, 30-40% in offices. Due to building regulations and requirements for labelling policies, the modern office building is seen as an "efficient machine", and energy consumption is becoming a central issue in the current architectural debate. However, also occupants' perception of indoor environmental quality (IEQ) should be verified. Therefore, new strategies for long-term building monitoring are required, focusing on human requirements and responses.

The present study describes a methodology (RPM = Remote Performance Measurement) to evaluate IEQ (measured and perceived) and its effects on comfort and performance in intervention studies in real buildings. The procedure comprises measurements of environmental parameters and completion by occupants of on-line questionnaires. Performance is assessed by a new method that uses simulated office tasks. Questionnaires and tasks are administered via a standard internet web browser?

The main objective of the research is the implementation and the validation of the method in field experiments. Thus, it was applied during the summer of 2004, in a case-control intervention study in a real office building, situated in Northern Italy. Measurements were carried out and questionnaires and performance tasks were completed prior to and after controlled modifications of specific HVAC system parameters, which affected thermal environment and IAQ.

Physical measurements of comfort indexes in the monitored building indicate indoor thermal conditions within comfort limits (ISO 7730-94). Nevertheless people's complaints point out local problems of thermal discomfort. Evidence of how raising room temperature set-point negatively affects the performance of an addition task was found, confirming the results of previous studies, showing how indoor environment factors also affect occupants' symptoms and performance. Occupants' feed-back, problems and possible improvements of the methodology are discussed. Furthermore, results of comparisons with contemporaneous and subsequent research are presented.

KEYWORDS:

Office work, comfort, productivity, field intervention, temperature

INTRODUCTION

In present-day society, people spend 90% of their time in enclosed spaces, 30-40% in offices: due to building regulations, introduced in many countries, and requirements for labelling policies, the modern office building is seen as an "efficient machine" and energy consumption in buildings is becoming a central issue in the current architectural debate. However, not only should the consumption of energy used to climatize and ventilate buildings be verified, but also the indoor environment and occupants' perception of the indoor environment quality (IEQ).

Previous studies have shown that indoor environment factors, such as air quality or temperature, affect not only occupants' perceived IEQ, but also their symptoms and performance (Wargocki et al., 2000; Toftum et al.,2005), reducing absenteeism, Sick Building Syndrome (SBS) symptoms and other complaints (Milton et al., 2000; Sundell et al., 1994). Immediate effects on occupant performance have been identified in call-centres, where the recording and storage of employee output is a standard procedure (Federspiel et al. 2004; Tham 2004; Niemelä et al. 2002), and in well-controlled studies in simulated offices using simulated office work (Toftum et al., 2004; Wargocki et al., 2000, 1999). However, due to the complexity of measuring the output of office work in practice, no feasible method for the measurement of office work performance has been validated so far. Thus, the overall cost-in-use of an office building should take into account not only energy consumption but also working costs and possible savings brought about by an

increase in productivity.
In spite of the extensive research on this topic, thermal environment and indoor air quality are still the main causes of complaints among office workers (Federspiel, 1998). New strategies for long-term building monitoring are required, focusing on human requirements and responses.
This paper describes the results of the research aimed to develop and assess a new method to evaluate IEQ (measured and perceived) in offices and its effects on occupants' health, comfort and performance, in intervention studies in real buildings. The procedure comprises measurements of environmental parameters, including - but not limited to - thermal parameters, IAQ, CO_2 and completion by occupants of on-line questionnaires. Questionnaires and performance tasks are administered over the internet, using a procedure recently developed by the International Centre for Indoor Environment and Energy (ICIEE) in Denmark: Remote Performance Measurement (RPM). To date, the method has been tested in buildings in Denmark and Italy. Preliminary results obtained in the first field application are presented in this paper.

REMOTE PERFORMANCE MEASUREMENT

RPM is the result of Professor David Wyon's (ICIEE) attempt to develop an easy, practical and standardised tool to assess office work performance, and is based on the Occupant Satisfaction Survey (OSS) devised by the Centre for the Built Environment (CBE) at the University of California in Berkeley.
The RPM version used in the present study consists of a set of standard tasks (which have been successfully used in simulated offices during laboratory experiments) and two different questionnaires (in English and Italian) that are used to characterize occupants' perceptions and symptoms.
The Background questionnaire focuses on occupants' general perception of the indoor environment (e.g. during the previous three months), while the Instant questionnaire focuses on conditions "right now" and is used to assess the effects of an experimental intervention that modifies environmental conditions in the working space: simultaneous measurements of physical parameters are therefore required.
Office work entails a wide range of different tasks involving a complex set of component skills: rule-based logical thinking, open-ended thinking, vigilance, persistence, concentration, effectiveness, effort, responsiveness/alertness, communication, short-term memory, accuracy, adaptability/flexibility, motivation, comprehension/understanding, analytical skills, planning and organization… Tests most commonly used by the ICIEE to simulate office work are based on a subset of these elements, in order to assess the performance using few, comparable parameters such as speed and accuracy. Although the listed skills may not be equally sensitive to or affected similarly by the indoor environment, it may be reasonable to assume that if these skills are affected by changes in the indoor environment, office work including these skills will be affected.
As it may be difficult for employees to allocate long periods to complete the tasks and their level of motivation might also decrease over time, only some of the available tasks have been selected in the present study: addition, text typing (already used in previous studies but not on-line), and short-term memory test.

Addition

The Addition Test assesses the ability to do mental arithmetic as a paradigm of rule-based logical thinking. The subject attempts to perform as many additions (four two-digit numbers) as possible during the available time of 5 minutes. The numbers are generated at random and contain no zeros. Performance is defined in terms of number of additions completed per time unit and the percentage error rate. After the test, occupants are asked if a calculator was used to perform the task, as in that case the cognitive task of performing mental arithmetic was not involved and was simply replaced by the trivial task of entering numbers on keyboards.

Text typing

The Text Typing Test evaluates the subject's ability to type fast and avoid mistakes. Additionally, it evaluates the subject's ability to read, memorize and transcribe, including keyboard skills.
The subject types a given text (taken from popular science magazines) exactly as shown on the screen. No importance should be given to the text format or layout, but the difference between upper- and lower-case letters should be retained. The available time to complete the Text typing is 6 minutes. For the whole duration of the text typing task, performance measures are derived: number of characters typed per minute and an error rate. The error rate is determined by Levenshtein's Distance (LD), which is a measure of the similarity between two strings, as "shortest edit distance" (Levenshtein 1966), which is the smallest number of deletions, insertions, or substitutions required to transform the typed text into the original text given on the screen.

Short-term Memory Test

The Short-term Memory Test, derived from the Sternberg's experiment (1966), has been developed in two versions: number or text comparison. It assesses the short-term memory of the subject through number and text checking. The subject's task is to determine whether two alphanumeric sequences of characters are identical, as quickly and accurately as possible. The character strings to be compared appear in different windows and the subject can toggle between them an unlimited number of times and assess if the number given in the following window is the same or if it is different from the one shown in the previous window. The pairs of strings arbitrarily differ in 50% of the cases.

FIELD APPLICATION

RPM is a very flexible tool, which can be easily adapted to meet specific experimental requirements.
This method is based on the ASHRAE measurement protocol, developed and applied in many campaigns to assess thermal comfort in office buildings located in different climatic regions (Cena and de Dear, 1998). The introduction of IT technologies – used in the present study - has deeply affected the above-mentioned procedure: time and modality of filling in questionnaires and performance tests have been changed, in order to coordinate internet connection and measurements of physical parameters. Questionnaires and performance tests have been modified too.
Since temperature and air quality are the most important factors affecting occupants' comfort and productivity, the present study aimed to validate the proposed method by a field experiment based on controlled changes of these two parameters (Witterseh et al., 2004).
The experiment took place in the new Permasteelisa Headquarter and was supported by the company, interested in assessing the quality of the working space in the new building - innovative in terms of façade and HVAC. The office building is located in the municipality of Vittorio Veneto, in Italy. Built in 2003, it has three storeys above ground and one more below, all of the same size and rectangular in shape. It has a double-skin envelope enclosing both the main sides facing south-west (public front) and north-east (productive area).
The central core of the complex hosts the entrance hall, reception, service spaces and the president's office. The two symmetrical wings (Building A, south-eastern wing, and Building B, north-western wing) are occupied by designers and administrative staff. External walls facing north-east and south-west are covered by double-skin façades with internal ventilation, distributed by Permasteelisa S.P.A. (Interactive Wall®). The south-east and north-west sides are made of lightweight concrete, plastered and painted white. The floors are covered with a wall-to-wall carpet of synthetic material. The false ceiling is made of radiant panels, with plastic heating/cooling pipes embedded in the external plasterboard, and internal insulation. The office environment measured is located on the first floor, in the wings of the building. It consists of two open-space office rooms, one in Building A and the other in Building B, with symmetrical plan and the same floor surface of 996 m^2, including the adjoining spaces (single offices, meeting rooms, toilets, service spaces). In each of these two office spaces there are ca. 70 workstations (only partially used), with only a few differences in the spatial layout. In Building A, where the experimental interventions were run, the whole space was investigated. In Building B, instead, the zone of interest was limited to the north-western half (external) of the room, where 30 employees were working. In the offices, the radiant ceiling (FCC, Planterm®) provides both heating and cooling, while neutral air is supplied by displacement ventilation. The conditioned air is let in by

displacement wall-diffusers (design supply air velocity of 0.25 m/s) located along the central corridors. Exhaust air is removed through the false ceiling, which serves as a collecting tank, by means of suction grilles placed near the external perimeter.
The experiment was designed as a "case-control intervention study", with interventions on the HVAC system in order to obtain different and specific indoor climatic conditions. Measurements were continuous throughout the whole 7-week period (12/06-29/07/04) and simultaneously performed in Building A (case-office) and in Building B (control-office). The setting of HVAC plants was altered, throughout three consecutive weeks (05-23/07/04), to obtain different experimental conditions: during the second week, the radiant ceiling was running with low cooling capacity, while cold air was supplied (design ventilation rate); in the third week the cold radiant ceiling was fully working, together with neutral air (design ventilation rate); in the fourth week, instead, the system was running with the same setting but reduced ventilation rate. During the two weeks before and after the interventions the system was running in standard operation mode, to collect reference data. During the fourth week the worst indoor condition was recorded (operative temperature of 24.7°C and air flow rate of 16 l/s person), while in the last week it was the best one (operative temperature of 22.6°C and air flow rate of 36 l/s person). Since the method is based on the comparison between instrumental and subjective measures, during the measurement campaign three main types of measurements were performed: instrumental measurements of physical parameters (mobile measurements, fixed measurement points, CO_2 and HVAC monitoring; in addition, outdoor climate data were collected), post occupancy evaluation questionnaires and performance tests.

RESULTS

During the first week of the monitored period the system was let running in standard condition, with a set point for operative temperature at 23°C. In the second week the system, in Building A, was expected to run with cold air and almost neutral radiant ceiling. That happened only in part, because of a rise in outdoor air temperature that inevitably affected air inlet (22.1°C). Therefore, the 1°C increasing of mean radiant temperature (23.4°C) produced a similar rise of operative temperature (24°C), not being compensated by cool air. The third week was meant to have opposite system conditions: Neutral air (23.8°C) was supplied to the open space in Building A, together with a very cool ceiling surface (18.8°C). That produced a low operative temperature (22.6°C), however accompanied by external rather low air temperature (22.9°C).

Table 1. HVAC monitoring resume

Date	Week	Condition	Outdoor T°	sky	Air T° (°C)			Air flow rate	Airflow per person	Air T°	Ceil. Surf. T°	TMR	Op. T°	CO_2 open sp.	CO_2 exh. air
			(°C)		air inlet	air exhaust	people	(m^3/h)	(m^3/h)	(°C)	(°C)	(°C)	(°C)	(ppm)	(ppm)
1/7	1	standard	25.4	1/8	21.7	24.3	52	4294	78	23.8	19.2	22.3	23.1	434	227
9/7	2	cool air 20% pan.	25.9	1/8	22.1	26.2	48	4294	84	24.6	21.3	23.4	24.0	266	208
15/7	3	neutral air panels on	22.9	1/8	23.8	24.7	47	4294	88	23.5	18.8	21.8	22.6	380	159
22/7	4	neutral air panels on	29.6	1/8	25.5	26.8	44	2735	59	25.5	21.0	23.9	24.7	476	509
29/7	5	standard	23.1	2/8	19.5	24.6	31	4294	130	23.3	19.4	22.0	22.6	311	123

In the fourth week system settings were the same but with reduced air flow rate (three chillers running with their fans on, instead of five) for Building A. However, there was an unwished rise both in air inlet (25.5°C) and ceiling surface temperatures (21°C). Air was anyway kept neutral, but that caused a 2°C operative temperature increase (24.7°C). Once more, external temperature raised as well (29.6°C). Eventually, in the fifth week the system was drawn back to standard condition for Building A. That meant actually lower air inlet temperature (19.5°C) than in the first week (outside temperature was also lower: 23.1 °C). Ceiling (19.4 °C) was almost equal and thus operative temperature decreased (22.6 °C). In Table 1 are listed the average values of the most significant physical variables measured for the five weeks. CO_2 concentration was measured both in the open space and in air exhaust ducts. Values shown in the table are already subtracted of the outdoor CO_2 average concentration.

The Background questionnaire was filled in by 56 people (10 women and 45 men) for group A and 28 people (3 women and 25 men) for group B. Nearly all those involved were Italian native speakers and 80% of them were technicians. However, due to volunteer participation, the number of participants during the five weeks was extremely fluctuating. For the above reasons the results were analysed twice, that is first taking into account all the participants and then limiting the selection only to those who had taken all the tests, in order to reduce sample variance.

Comfort indexes show that thermal conditions in the working area, although related to external climate, complied with international standards (ISO 7730-94) and the air flow rate was always above Italian standard limits (UNI 10330-95). Even so, the participants expressed a feeling of thermal discomfort. Figure 1 shows the thermal sensation along the 5 weeks, showing the combined effect of planned events and external thermal conditions: thermal sensation expressed by participants was consistent with the changes in indoor climate (Figure 2), as well as the acceptance and the preferences regarding the thermal environment (Figure 3).

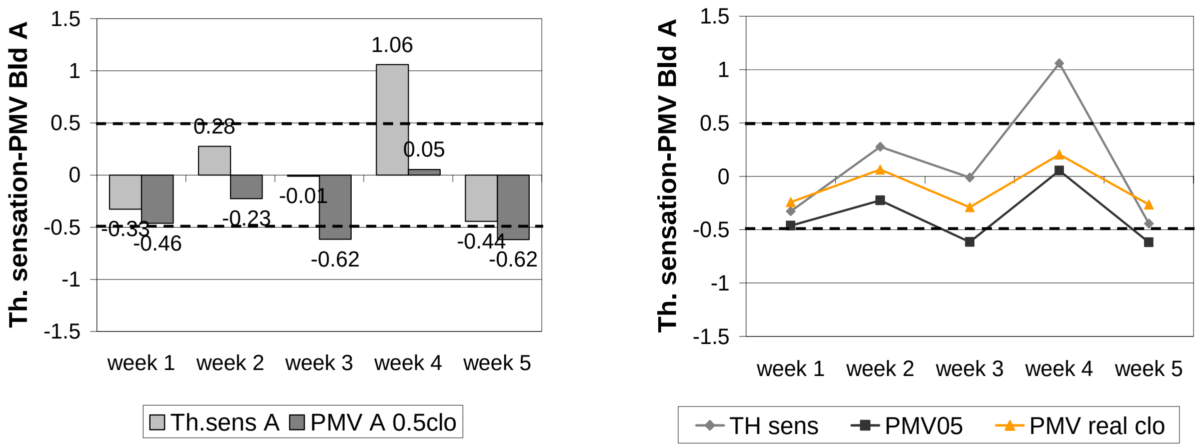

Figure 1. Thermal sensation and PMV (I_{cl}=0.5 clo on the left; I_{cl}=0.5 clo and I_{cl}=clo effective on the right) in 5 test conditions (Group A: all subjects)

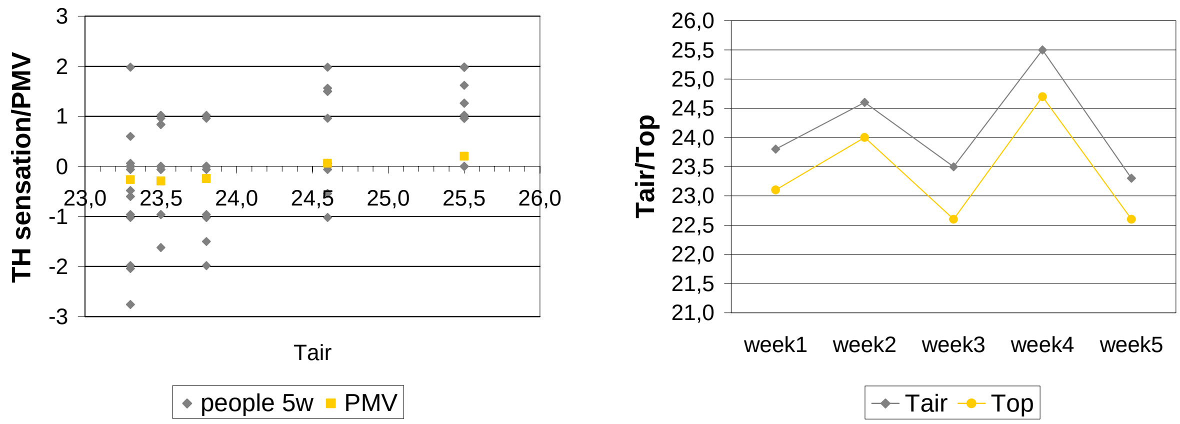

Figure 2. Relation between thermal sensation and measured air temperature for each individual who completed the questionnaire in each of the five weeks (Group A)

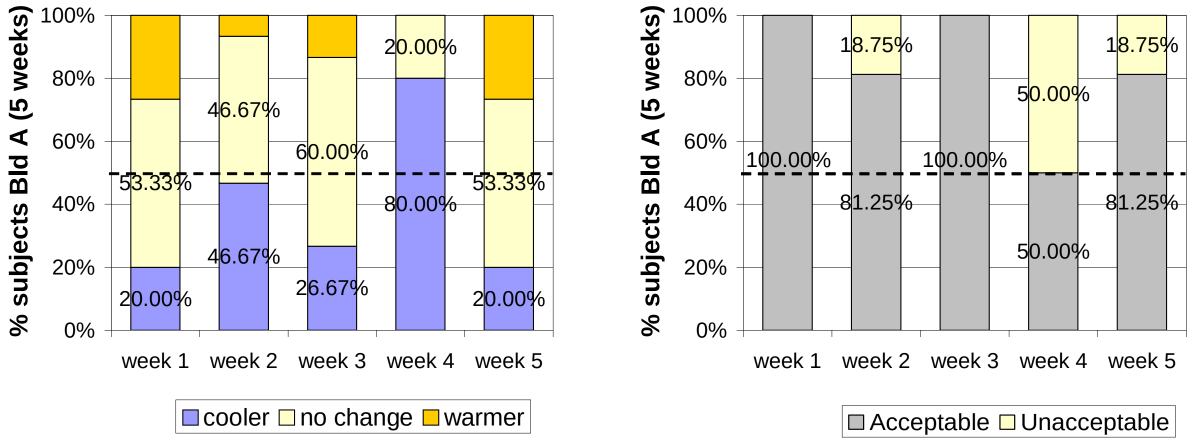

Figure 3. Thermal preference and acceptance of the thermal environment (Group A: selected subjects)

Due to the features of the HVAC system, with displacement ventilation and radiant panels, air velocity was always quite low: Figure 4 shows how the percentage of people complaining about draught was always below 15%, i.e. the maximum limit of people dissatisfied with draught (DR) accepted by ASHRAE 55-92. The only exception was the first week, when the percentage reached 25%, corresponding to the limit indicated by CEN CR 1752-98, for ambient type C.

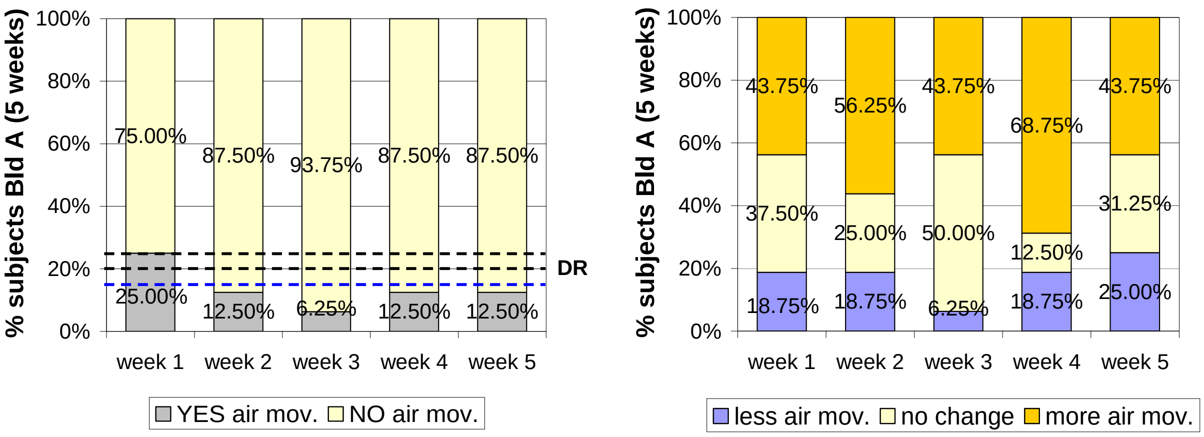

Figure 4. Perception of draught and preference vote (less air movement, no change, higher air movement) (Group A: selected subjects)

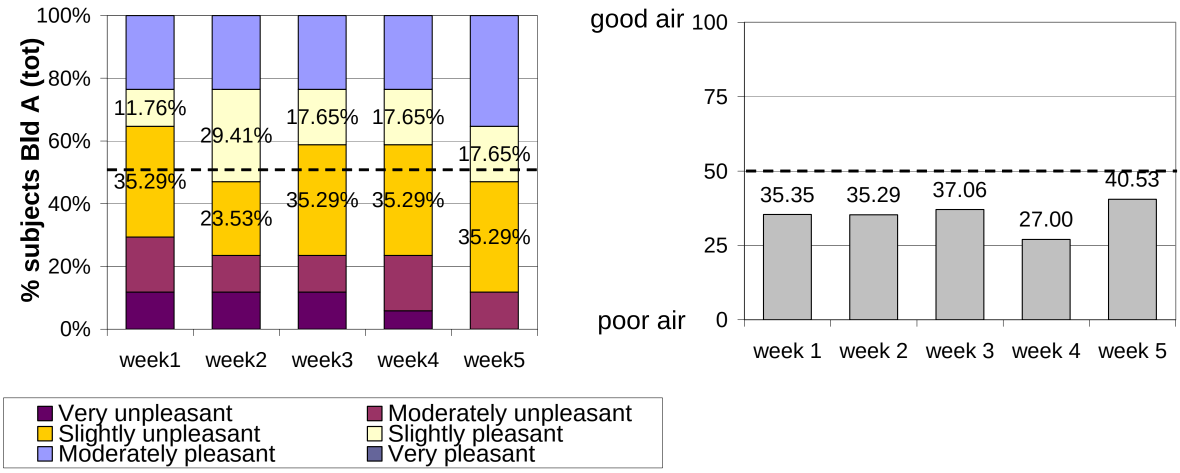

Figure 5. Perceived air quality (Group A: selected subjects)

Despite air flow rate always being above the standard limit of 11 l/s per person (UNI 10339-95), the occupants' response showed a different perception of air quality in the fourth and fifth week, corresponding to the higher and to the lower air flow rate (Figure 5).

Significant differences among the experimental conditions concerning SBS symptoms were not demonstrated, apart from the general feeling of malaise expressed by the participants of group A, higher in the fourth week (warmest environment) than in the first ($p<0.02$), third ($p<0.04$) and fifth ($p<0.02$).
On the contrary, the experiment showed effects of the temperature on self-estimated performance: the subjects rated their work as less efficient in the second and fourth week, characterized by a higher room temperature.
Clear evidence of the effect of thermal conditions on the performance during the addition test was found (Figure 6). From the analysis of the data concerning the percentage of error, significant differences emerged only between the first and the fourth week ($p<0.03$): the percentage of error increased in the fourth week, as expected, due to the worst experimental conditions. With an increase in operative temperature from 23.1 °C to 24.7 °C and an air flow rate reduction to 2/3, the percentage of error increased by 35%.
Considering the index of speed (number of additions per minute), significant differences were found between the first and second week ($p<0.005$), as well as the third ($p<0.001$), the fourth ($p<0.001$) and the fifth ($p<0.001$), due to the learning effect, as demonstrated by the Page test. Interesting indications emerge from the analysis of the results on the speed of execution: eliminating the first week from the analysis, definitely affected by the learning effect, the best performance was observed in the third and in the fifth week, whereas the worst was observed in the second and in the fourth week, even though the quantitative interpretation of the results is quite difficult.

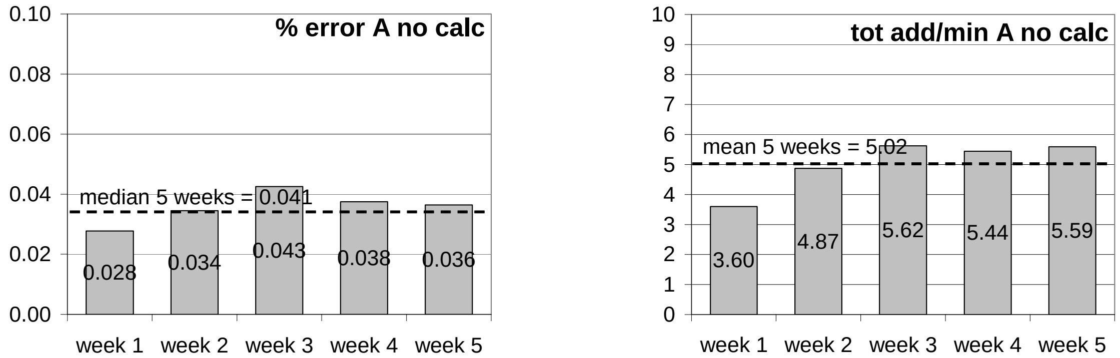

Figure 6. Addition Test without calculator: average values of the two indexes, percentage of error and number of additions per minute (Group A: selected subjects)

The performance during the text typing test, on the contrary, was not affected by changes in environmental conditions, whereas the short term memory test proved to be sensitive to changes in thermal sensation (Figure 7).

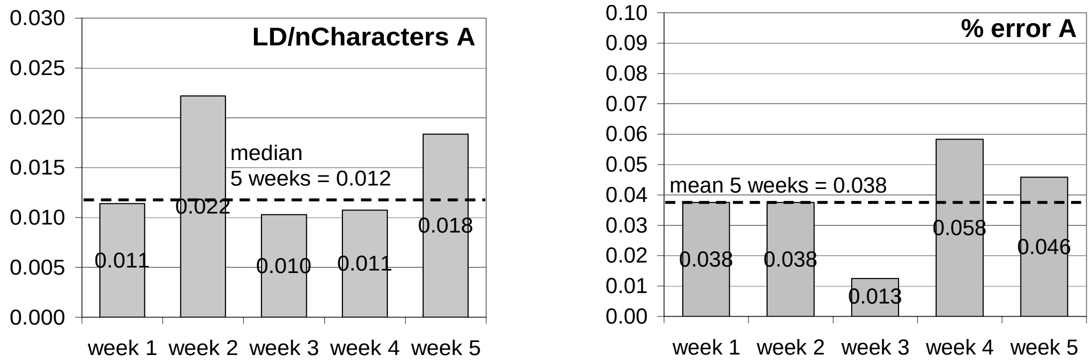

Figure 7. Results of the test typing test, related to accuracy, and of the short term memory test, related to the percentage of error (Group A: selected subjects)

DISCUSSION

The study shows how the method may provide detailed information on physical characteristics and subjective perception of the working environment – from the thermal, acoustic and visual point of view, as well as perceived air quality, ergonomics, human relations, etc – and not least their impact on occupants.
The use of questionnaires for the subjective assessment of the working environment allows collecting information in addition to that given by mere instrumental measurements, thus highlighting problems not easily detectable in other ways, such as those connected to local discomfort.

Compared to previous studies, focusing on single environmental parameters or on the combined effect of some of them, this method enables simultaneous collection and comparison of information on different environmental factors, taking into account the complexity of a real working space (not reproducible in simulated office environments or in climate chambers).

Since temperature and air quality have documented effects on human performance, it was initially decided to validate the RPM approach in an intervention study, setting different experimental values of these two parameters (Wyon, 2001, Wargocki et al., 1999). The method, however, allows for less control than in simulated office environments (since it is more difficult to obtain and maintain the desired experimental conditions) and only a limited opportunity of assisting and instructing occupants. In the present study the effect of the indoor climate was also affected by the outdoor climate. Therefore, it was not possible to reach exactly the desired indoor conditions. Nevertheless the disturbing effect of the outdoor climate was accounted for in both the physical measurements and in the resulting subjective responses.

The combined effect of different environmental parameters, typical of real working environments, does not affect the effectiveness of the proposed method, but, in this experimental phase, makes validation more difficult, probably requiring new and repeated verifications. Despite the limitations of the control system, the experiment provided valuable results, in particular considering the minimal differences between the experimental parameters recorded.

The changes in thermal sensation – corresponding to the measured operative temperatures – correspond well with the subjective assessment of thermal preference and acceptability. The increase in operative temperature from 22.6 °C (in the third week) to 24.7 °C (in the fourth week) reduced thermal comfort – estimated by the thermal sensation – sharply decreasing the percentage of subjects that perceived the environment as comfortable (from 53% to 13%) and did not wish for any changes (from 60% to 20%). Overall, the acceptability of the thermal environment dropped from 100% to 50%.

The information gathered using the Instant questionnaire also showed local discomfort among the occupants. Compared to the small amount of subjects that complained due to radiant asymmetry, a higher percentage of people felt thermal discomfort because local parts of the body were cold or hot.

The air flow rate was generally above the standard limit, but its increase from 16 to 36 l/s per person in the last week, compared to the fourth week, resulted in a 20% reduction of subjects that judged the air unpleasant.

The CO_2 concentration depended on the ceiling temperature and as such on the efficiency of the displacement ventilation system. As the distribution of carbon dioxide concentration suggests, the contaminant displacement works properly for ceiling surface temperatures higher than 21°C.

No significant effects on the intensity of SBS symptoms of temperature reduction and airflow rate increase were demonstrated. It is necessary, however, to keep in mind that SBS symptoms typically arise after longer occupancy and therefore it is possible that, in the present study, the exposure prior to completing the survey had not been long enough. Although not significant, some symptoms showed up quicker than others: depression, difficulty in concentration, lethargy and uneasy feeling were higher in the fourth week compared to the fifth week.

The experiment showed effects of the temperature on self-estimated performance. The results support the findings of Witterseh et al. (2004), where thermal discomfort, corresponding to an environment classified as “slightly warm”, reduced self-estimated performance.

In spite of the lacks of statistical evidence and considering only the subjects who executed the task without calculator, the results indicated effects of environmental conditions on the performance in the addition test. The calculation speed was higher in the third and in the fifth week, characterized by a lower operative temperature, compared to the fourth. In particular, comparing the fourth and the fifth week, that represented the extreme conditions, with a reduction in air temperature from 25.5°C to 23.5°C in the last week, an approximate 3% increase in execution speed was recorded and, at the same time, a 5% reduction in the percentage of error. No statistical differences between experimental conditions were found for subjects using the calculator, confirming the results of Toftum et al. (2005). In their study, when the task did not require any particular mental effort, temperature level did not affect performance, but when occupants themselves performed mental arithmetic, their performance decreased in the warmest environment. The results also may depend on the reduced sample size, caused by subjects not consequently carrying out the task either with or without calculator.

Although experiments carried out in simulated offices demonstrated that the performance of a text typing task was sensitivity to air quality (Wargocki et al., 2000), in the present study (with time for the execution of the task reduced to 6 minutes and airflow rate always above standard limits) no effect of air quality on performance was found. Similar findings appeared in the study by Toftum et al.. (2005) and Witterseh et al. (2004).

The present study indicates instead a particular sensitivity of the short term memory test to changes in operative temperature, when occupants’ thermal sensation changed. The lowest percentage of error was recorded in the third week, characterized by a neutral thermal environment, while the highest one was recorded in the fourth week that is in a “slightly warm” environment. The analysis, however, suffers from a learning effect on the performance (as demonstrated by the Page test), which was not possible balance out due to the absence of a control group – being environmental conditions in Building B (control office) not comparable with those in Building A. Ideally, a study of this nature should be carried out in a cross-over design. However, for practical reasons, this was not possible and case/control design was aimed at instead. However, the number of responses from the control group was too limited to be used in the analysis, and therefore the results of the study should be seen as a demonstration of the opportunities of using RPM for evaluation of occupant responses and performance.

CONCLUSION

The study has led to the development - and the first field application - of a new method to assess indoor environmental quality in office buildings, and to measure its effects on health, comfort and work performance of their occupants. The research outcomes are unavoidably connected with the specific case-study and therefore should be seen as a demonstration of the methodology rather than a final documentation of IEQ effects on performance in practice. Also the physical parameters of the cooling plant were clearly related to the outdoor air temperature. Therefore the attempts to modify the HVAC system settings and thus the indoor environment did not result in the desired conditions.

In general, the current study confirmed the effects of environmental conditions on occupants' comfort, emerging from earlier laboratory studies. The developed questionnaires showed their effectiveness in collecting detailed information on personal judgment, degree of acceptability of the environment and of occupants' perception of many different factors (temperature, air quality, etc.).

The intensity of some specific and general SBS symptoms was slightly affected by the thermal environment, although this still needs to be verified statistically. A difference in self-estimated performance was also detected.

The quantity and quality of the data collected and the results found indicate the substantial effectiveness of the proposed method, with particular regard to its most innovative aspects, such as on-line implementation and the simultaneous collecting of instrumental and subjective information. However, the field application of the method highlighted some inconsistencies and problems, related above all to the procedure, in particular to times and modality of the administration of questionnaires and performance tests. Therefore, although somewhat trivial, suggestions for future application of the method are given in the following: Preliminary inspection of the building prior to the monitoring campaign (to collect building and system data); apply questionnaires and performance tests a limited number of times and only during short intervals (to avoid a reduction in motivation); control access to surveys and performance tests; preventively establish population sample according to the chosen experimental design and the desired level of significance; hold an introductory session for the subjects involved in the experiment; adaptation of the performance tests to the work carried out in the company.

With these suggestions and future improvements of the test and questionnaire batteries, additional and qualified data may add to the state-of-the-art of relations between IEQ and human comfort, health and performance.

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