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ScienceDirect

Energy Procedia 78 (2015) 3126 – 3131

Energy Procedia

6th International Building Physics Conference, IBPC 2015

Overall indoor quality of a non-renewed secondary-school building

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Abstract

This work is the result of a field study about overall comfort aspects performed in a secondary-school building during the winter season. The campaign aimed at describing the conditions of the school both from an objective and a subjective point of view, thus a questionnaire was administered to pupils during ongoing lessons. The monitored attributes concerned typical indoor quality aspects: acoustical, thermal, indoor air and visual quality. Weak points emerged from the data analysis and possible solutions are illustrated, focusing in particular on the acoustic aspects.

Peer-review under responsibility of the CENTRO CONGRESSI INTERNAZIONALE SRL

Keywords: educational building; overall indoor quality; acoustic characterisation; room acoustics; building acoustics

1. Introduction

It is well known that a good indoor quality is a necessary requirement for an educational buildings [1]. Many studies have investigated indoor conditions of schools because of its close relation to students' attention, productivity and learning attitudes [2] together with teachers' health. The literature provides different kinds of studies: many studies focused on one or two environmental conditions [3], while others were oriented to a holistic approach [4]. For this study, the chosen perspective was to monitor all physical factors (acoustical, thermal, indoor air and visual), even if focusing in particular on the acoustic aspects, with the aim of capturing the indoor aspects that could interfere with students' attention. An attempt was made to weight the importance of each element asking students (thirteen to fourteen year old) to complete a questionnaire about their level of satisfaction with the

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Peer-review under responsibility of the CENTRO CONGRESSI INTERNAZIONALE SRL
doi:10.1016/j.egypro.2015.11.768

classroom indoor conditions: possible annoyance causes were investigated as well as the way students interact with their environment to react to discomfort.

The school was built in the early '70s; it has an articulated plan, spreads over three levels and it is characterized by a concrete structure and ribbon windows shaded by projecting concrete elements. Given the modular structure of the building, classrooms have an almost constant size (floor area 58 m^2, volume 172 m^3). This non-renewed secondary-school building is exploited as a case study: a repeatable measurement procedure is described and applied.

2. Investigation methods

2.1. Objective survey

Room acoustics measurements were performed in unoccupied and furnished classrooms in order to guarantee repeatability. The acoustic criteria were evaluated from impulse responses (IRs) measured using an MLS signal. All measurements were performed following the ISO 3382 guidelines [5] as a minimum target and a statistical analysis was conducted for the criteria EDT, T_{20}, C_{50} and C_t in the octave frequency from 250 Hz to 4000 Hz. The IRs were measured using three sound source positions (teacher desk, centre and corner of the listening area) and eighteen microphones positions (height 1.1 m) throughout the classroom. Occupied values of reverberation times where evaluated at a later stage accordingly to UNI EN 12354-6 [6]. Intelligibility measurements were performed using a NTI TalkBox loudspeaker that provided a human-like test signal with a sound pressure level of 60 dB(A) [7] and an NTI XL2 analyzer for evaluating the STI parameter. The measurement setting comprised the sound source behind the teacher's desk and six representative receiving points in the room. Building acoustics measurements included: façade sound insulation, impact sound insulation and airborne sound insulation of representative sample of building elements [8]. Environmental monitoring [9] took place during the heating period in five rooms, during morning classes: air temperature and relative humidity (RH) were measured with a DH206-2 Delta-Ohm data-logger with a time step of one minute (accuracy: 0.3°C for temperatures; 2.5% for RH), put on a student's desk in the center of the room (0.75 meters above the floor). Measurements performed with the Thermal Microclimate HD32.1 completed the survey by measuring air temperature (t_{air}), globe thermometer temperature, relative humidity (RH), air velocity (v_{air}), CO_2 concentration and desk illuminance (E_{mean}).

2.2. Subjective survey

A questionnaire was designed starting from the inherent literature and paying attention to the respondent's target [10][11][12]. Some simple but effective principles were followed in order to improve response quality and reliability. Items were kept as simple as possible, all questions options were completely labeled and they were often supplemented by pictures and colors, trying to keep pupils motivated to answer. Before its administration, the questionnaire was first validated and then submitted to the teachers' supervision. The final version contained forty- five questions organized in five sections: the first was about general information and overall impressions about the indoor environment, while the remaining four covered respectively acoustical, thermal, air quality and visual attributes. The acoustical quality section investigated noise sources, their intensities, their frequency of occurrence and their degree of annoyance. Besides pupils had to evaluate room reverberation and speech intelligibility [13][4]. The thermal quality paragraph concerned the perception of the thermal environment [14]: a seven point scale was used both for the thermal sensation [15] and for thermal preference, while a separate judgment was asked for acceptability and students' reactions to discomfort. Air quality questions investigated whether the air was dry, dirty, characterized by any smell and if the student are used to open windows to ensure the air exchange. At last the lighting section regarded the quality of light (both natural and artificial) on the blackboard, on the multimedia board and on respondents' desks. Students were asked to fill in the questionnaires thinking about the whole heating period and the conditions that they experience in their classroom when seated at desk. The sample size consisted of 105 thirteen years old pupils, on average, with a 52% of females and a 48% of males.

3. Results and discussion

3.1. Acoustic measurements and possible acoustic treatments of rooms

The old Italian regulation [16] requires for schools a mean reverberation time smaller than 1.2 s in the octave bands from 250 Hz to 2000 Hz in unoccupied conditions, while the regulation [17] introduced, as design criteria, an optimal reverberation time that depends on the room volume and sound frequency ($T_{ott} = k_f(-0.2145 + 0.45\log V)$). UNI 11367 [18] gives a further reference as a function of volume as well ($T_{ott} = 0.32\log V + 0.03$); in each frequency band values should never exceed $1.2 \times T_{ott}$. All of the classrooms have the same volume of about 172 m^3 and should require a mean unoccupied reverberation time of 0.87 s or 0.75 s following the two mentioned relations, but it never happens. Italian law does not suggest any other speech quality criteria. Useful but not mandatory indications are found in UNI 11367, where the speech clarity (C_{50}>0 dB) and the speech transmission index (STI>0.6) are considered. Tab. 1 gives a summary of room acoustics: the limit values are not respected and a non- uniform distribution was found. Tab. 1 provides an estimation of the reverberation time in occupied conditions following [6]. Interestingly only 10% of pupils found the room too reverberant, 53% did not know how to judge this aspect and the remaining believed the room not reverberant. Probably the students did not understand properly the concept of “reverberation” (an unusual term in Italian). 83% of them answered to be able to hear well or very well the teacher’s voice albeit measured STI value without noise was 0.52, between “poor” and “fair” [7].

For building acoustic requirements, the DPCM 5/12/1997 [19] establishes limit values for school buildings and UNI 11367 [18] sets performance classes. It is worth noting that the latter complements the DPCM taking into account internal partitions too, as it should be expected dealing with learning spaces. The measurements results are summarized in Tab. 2 together with the limit values; the arithmetic mean is underlined when it does not comply with the DPCM. As the performances are not satisfactory, some solution should be envisaged for this case study. Two 3D simulation models were set up and tuned: one in Namirial Acoustics© for building acoustics and the other in Odeon© for room acoustics. Measurements and inspections revealed that requirements were not always met due to unsuitable or outdated constructive solutions. The sound insulation performances of party walls and of the façade are impaired by the partition-frame junction, by the false aluminium sheet pillars with an uneven filling of polystyrene beads, by the symmetrical double glaze windows (3+1+3) and by the discontinuity of the panels of extruded polystyrene foam. Besides, floor has adequate mass but lacks in a resilient layer. Hence it was considered appropriate to install on party walls a soundproof lining (0.95 cm plasterboard + 3 cm rock wool panel, about 10 kg/m^2) and on floors a screed of 4 cm on a layer of resilient material (about 77 kg/m^2 overall). A complete replacement of fixtures would also be helpful to reduce acoustic bridges and coincidence phenomena. These solutions were all included in the numerical model of the whole building and they were all found useful. Room acoustics measurements revealed excessive reverberation times and a lack in clarity and speech intelligibility. The easiest solution would be to install ceiling panels in order not to interfere with classrooms layout.

Table 1. Room acoustics criteria measured and estimated [*] in classrooms (mean value and range).

	250 (Hz)	500 (Hz)	1000 (Hz)	2000 (Hz)	4000 (Hz)
$T_{20,\,mean}$ (s) [range]	1.17 [0.91;1.48]	1.17 [0.92;1.42]	1.35 [1.14;1.59]	1.47 [1.24;1.74]	1.30 [1.16;1.53]
EDT_{mean} (s) [range]	1.10 [0.62;1.61]	1.16 [0.84;1.51]	1.34 [1.07;1.61]	1.47 [1.23;1.82]	1.30 [1.12;1.55]
$C_{50,\,mean}$ (dB) [range]	-5.48 [-12.90;1.10]	-5.87 [-12.94;2.04]	-5.55 [-10.53;-0.65]	-6.28 [-9.85;-1.72]	-5.74 [-8.58;-0.15]
$T_{60,\,OCCUPIED}$ (s) [*]	1.07	1.08	0.94	0.95	1.02

Table 2. Building acoustics measurements and reference values.

	Measure #1	Measure #2	Measure #3	Mean	DPCM 5/12/97	UNI 11367	
$D_{2m,nT,W}$ (dB)	32	26	27	28	≥48	≥38	≥43
$L'_{n,W}$ (dB)	71	68	69	69	≤58	≤63	≤53
$R'_{W,FLOOR}$ (dB)	52	50	53	51	≥50	≥53	≥63
$R'_{W,WALL}$ (dB)	44	43	45	44	≥50	≥53	≥63

Table 3. Costs of the acoustic improvement solutions for each classroom.

Type	Improvements	Required quantity	Unit cost	Total Amount
B.A.	Party walls lining	71 m^2	35.95 €/m^2	2 553 €
B.A.	Floating floor	2.6 m^3	371.71 €/m^3	967 €
B.A.	Windows	22.4 m^2	113 €/m^2	2 531 €
B.A.	Frames		123 €/m^2	2755 €
R.A.	Ceiling lining - #1	58 m^2	68 €/m^2	3 944 €
R.A.	Ceiling lining - #2	58 m^2	97.8 €/m^2	5 673 €
R.A.	Baffles - #3	20 m^2	298 €/m^2	5 960 €

The cheapest sound absorbing lining is made of polyester fiber panels 5 cm thick (#1), but this solution is not very durable and panels gets dirty easily. Ceiling plasterboard (#2) represents an effective alternative: it costs a little more but it is much more durable and requires little maintenance, which are not negligible aspects in schools. Acoustic baffles (#3) are another interesting solution: the twofold absorbent surface would allow a reduced installation area, thus an accurate placing would help to reduce the uneven spatial distribution of acoustic criteria, but it is really expensive. Room acoustics simulations proved the effectiveness of these solutions.

The above solutions and their cost are shown in Tab.3, where B.A. stands for building acoustics and R.A. for room acoustics. The costs of B.A. interventions would be about 8 800 € per classroom, instead R.A. solutions range from about 4 000 € to 6 000 € per classroom. It was decided to rank the interventions priority according to pupils' annoyance judgments concerning the most recurring noise sources (i.e. students in the room -SR-, students in neighboring rooms -SNR-, students in aisles -SA- and external road traffic -ERT-). The higher scores are those of SR and SA because they are considered louder (52%, 35%) and annoying (22%, 22%) according to a largest amount of students. However, it is interesting to point out that student's perception of annoyance is much more correlated with the frequency of occurrence of noises rather than with their intensity. Overall, it may be advisable at least to implement the current situation with party walls lining, new ribbon windows and plasterboard ceiling lining, in order to reach reasonable performances and to take into account the main pupils' claims.

3.2. Environmental measurements

The microclimatic parameters were analyzed in order to evaluate Fanger's indices [20] and the results were compared to pupils' impressions. The metabolic rate was set at 1.2 met due to students' sedentary activity while clothing insulation values derived from questionnaires (mean value 1.05 clo). The calculated PMV values showed almost neutral mean values in all the classrooms, but the extremes determined different categories [21]: category II for classrooms 3D and 3E, category III for 3A and category IV for 3B and 3C. Fig. 1 shows the distribution of both actual thermal votes (AMV), preferences and calculated PMV, sided by acceptability judgements. AMVs tend to be distributed slightly more on the cold side, while in this survey PMVs overestimate thermal votes. As expected the preference votes are almost symmetrically distributed if compared to AMVs, leading to a preferred neutral environment. It is interesting to focus on the wide acceptability range that emerged from the survey. Up to 36% of pupils considered acceptable a cool (-2) environment, 60% a slightly cool one (-1), 80% a slightly warm room (+1) and 50% a warm one (+2).

CO_2 concentration was found considerably high and only in two out of five classrooms the measured values did not exceed the basic requirements of 1500 ppm, but it is to say that windows were never opened during the measurement session, probably due to cold outdoor temperatures. Questionnaire responses followed the measurements trend: only 32% of the population is satisfied of air quality, 64% judged the air as bad and heavy, but at the same time almost all respondents affirmed to react actively to such a discomfort opening the windows.

Illuminance requirements (≥300 lux) were satisfied only in three out of five classrooms with the artificial light system switched off (it usually supplies these lacks and the non-homogeneous illuminance of rooms). This may be a cause of the large amount (30%) of unsatisfied students, comparable to the amount of those who complained about the thermal environment.

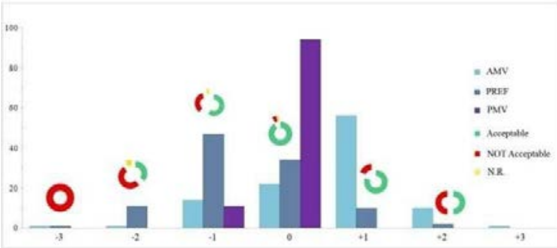

Fig. 1. Pupils’ answers about thermal environment (AMV) compared with their preferences (PREF) and measured PMV.

Table 4. Indoor conditions during the day of microclimatic monitoring.

	3A	3B	3C	3D	3E
Location & Orientation	1st floor; NW	2nd floor; NE	1st floor; SW	2nd floor; NW	ground floor; SE
# of students [boys;girls]	21 [10;11]	22 [14;8]	22 [9;13]	19 [9;10]	21 [8;13]
t_{air} (°C)	20.6	19.6	20.2	20.4	21.3
RH (%)	53	55	49	46	50
t_{op} (°C)	20.6	19.5	20.1	20.4	21.4
v_{air} (m/s)	0.01	0.01	0.01	0.01	0.01
PMV_{mean} [range]	-0.5 [-0.69;0]	-0.33 [-1.04;0.35]	-0.33 [-0.84;-0.13]	-0.13 [-0.34;0.5]	0.06 [-0.5;0.15]
AMV	-0.14	-0.55	-0.41	-0.68	-0.86
E_{mean} (lux)	241	231	627	535	540
CO_2 (ppm)	1936	n.d.	1480	1543	1972

3.3. Overall comfort: students’ perception

The subjective approach aimed at finding out correlations between pupils' perception and aspects that may be critical, relying solely on physical measurements. Hence, students were asked how they feel in their classroom and to rank the four quality aspects taking into account their influence on the overall satisfaction. Moreover, each section of the survey ended with two questions about the satisfaction for each single aspect and if it affects the learning activity. Purposely the word “comfort” was never used to avoid misleading answers or interpretations. The largest part of students (68%) said to feel “good” or “very good” in classroom, 31% answered with a neutral vote and only 4% of them answered “bad” or “very bad”. The most voted aspect, i.e. ranked as the most important, was the acoustic one (30% of votes), followed by the thermal (21%), the air quality (19%) and the visual (17%) aspect, as shown in Fig. 2-(a). What appears more interesting is the correlation of satisfaction and influence votes with overall satisfaction judgments, plotted in Fig. 2-(b). It clearly emerges that pupils’ votes are strongly correlated with the influence votes of both acoustic and visual aspect, while satisfaction votes have a different trend. The correlation with acoustic votes has to be linked to noise aspects because of collected responses about reverberation.

a b

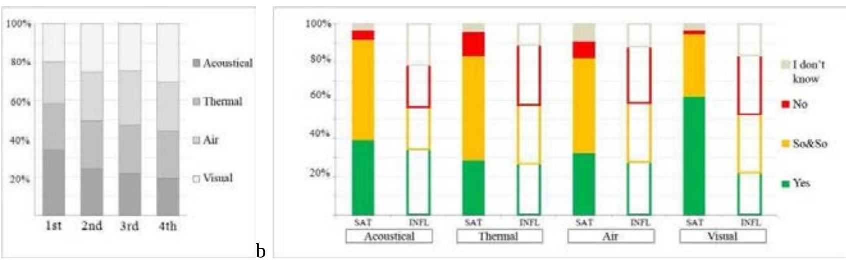

Fig. 2. (a) Overall satisfaction: pupils’ ranking of attributes; (b) votes of satisfaction and influence on learning performance.

4. Conclusions

The paper deals with overall indoor quality in educational buildings and a measurement campaign performed in a non-renewed secondary school building is exploited as case study. Measurement methods are outlined and results are discussed both from objective and subjective point of view. The building acoustics requirements are affected by outdated constructive solutions, classrooms were found too reverberant, lacking in clarity and with a low performance in supporting oral communication due to the acoustically untreated surfaces. CO_2 concentration was found too high because air changes depends on users only, and natural light alone does not comply with illuminance requirements. Questionnaires revealed that the acoustic and visual aspects play a key role on students' perception of their learning spaces. This is the typical outline of a non-renewed educational building. In this framework, acoustics is considered a noteworthy aspect that is often neglected both in the design and in the retrofit stages. Thus, improving solutions have been illustrated, comparing the alternatives on the basis of numerical simulations and a cost analysis. Albeit the suggested solutions may appear quite expensive, they would not in a perspective of whole building refurbishment. As a matter of facts, the school may need further intervention to get to reasonable energy efficiency and comfort standards. The carried out survey revealed a non-completely comfortable thermal environment and a non-uniform correspondence between AMVs and PMVs. This is worth of a future in depth analysis.

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