Ventilation Rates in Schools and Learning Performance

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SUMMARY

Associations between classroom ventilation and pupils' performance were investigated in primary schools in the United Kingdom. The concentration of carbon dioxide and other parameters were monitored for three weeks in two selected classrooms in each school. A direct air supply system through the windows was used to alter the ventilation rates in the classrooms. The system was set either to provide outdoor air or to re-circulate the classroom air while all other physical parameters were left unchanged. Computerised Assessment Tests and Paper-based Tasks were used to evaluate pupils' performance. Pupils' perceptions about the classroom environment, comfort, general mood and hunger were assessed on subjective scales. The present paper shows preliminary results obtained for one primary school out of eight being studied. Due to the intervention the fresh air supply increased from 0.3-05 to 13-16 L/s per person that increased pupils' work rate by ~7% in addition ($p<0.036$) and subtraction ($p<0.052$).

INTRODUCTION

Former reviews on the subject of school environments emphasised that ventilation is often inadequate in classrooms causing increased risk for asthma and other health-related symptoms among school children [1], [2]. Mendell & Heath [2] proposed that throughout the life of each existing and future school building immediate measures should be taken for the provision of adequate outdoor ventilation, control of moisture, and avoidance of indoor exposures to microbiologic and chemical substances considered likely to have adverse effects. The current ventilation standards and guidelines [3], [4] recommend a minimum fresh air supply rate of 8 litres/s per person for occupants in all teaching facilities. The recently published Building Bulletin 101 refers to proposed performance based standards limiting the level of carbon dioxide (CO_2) concentration to 1500 ppm over a full school day from 9:00 to 15:30 and specifies a minimum supply of external air at least 3 L/s per person in all teaching and learning spaces when they are occupied. Furthermore, a ventilation rate of 8 L/s per person for the normal number of occupants should be achievable under the control of occupants, although it may not be required at all times if occupancy level decreases. However, according to recent studies the average CO_2 levels in classrooms often exceed the above limit and ventilation rates are often below the minimum requirement of 3 L/s per person [5], [6].
The negative effects of poor ventilation rates on work performance in office buildings have been widely investigated [7]. Knowing the outcome of poor ventilation rates for the adult population it could be expected that not only the comfort and health, but also the learning performance of school children are affected by the poor environmental conditions in classrooms [2]. Following the earlier studies suggesting correlation between pupils' health

and work performance, [8], [9] there is growing evidence showing impairment of learning performance and increased absenteeism due to inadequate ventilation and unsuitable thermal conditions in classrooms [10], [11], [12], [13]. The main purpose of the present research was to investigate the relationship between pupils' health, well-being and performance, and the indoor air quality in several primary schools in Southern England. Another aim was to examine the suitability of the air quality guidelines in preventing the reported negative effects even when the recommended levels of fresh air to the occupants are met.

METHODS

Field surveys were carried out at primary school buildings located in the proximity of Reading during years 2006-2007. Up till now measurements have been done in eight different schools. The sample included schools that were built in the last 20-40 years. Except for one school, none of them had mechanical ventilation system and in most schools no control over the temperature was available to the staff. At each selected school investigations were carried out in two classrooms for at least three consecutive weeks. The first week was reserved to monitor the classroom conditions without modifying any of the indoor climatic parameters and to familiarise the children with the performance tests. During the second and third week a mobile ventilation system was installed in each classroom to control the ventilation rate and maintain the temperature within certain limits. The system was set either to provide outdoor air or to re-circulate the classroom air. Although the ventilation system was visible, the staff and the children were not informed of the ventilation conditions, i.e. whether it was providing fresh air or re-circulated air. The order of presentation of the fresh air/re-circulated conditions were made in a cross over repeated design for the two classrooms.

The ventilation system consisted of an exterior fan placed outdoors and simple ducting of diameter 200 mm led the air into the building through window openings, which were closed with Perspex plates (Figure 1, a). In the classrooms the air was distributed using Softflo air terminal units, which consist of a perforated duct with small nozzles creating confluent jets flow into the room [14]. The temperature of the supplied air was controlled by means of a duct heater (3kW) and a mobile air conditioning unit of 2.7kW built into the ventilation system. The capacity of the supply fan was selected to provide 200 L/s, matching the prescribed level of 8L/s per person in a classroom having on average 25 children. Silencers were also built into the system upstream and downstream of the fan to reduce the noise level propagating through the duct work into the classroom.

a)

b)

Figure 1. a) Exterior fan of the mobile ventilation system, b) Testing area with laptops and measuring trolley with the air terminal device in the background; the trolley was placed close to the testing area during performance tests.

Physical measurements: CO_2 concentration (0-5000 ppm), air temperature, globe temperature, relative humidity (RH), air velocity and light level were continuously monitored in each classroom and recorded with 3 minutes interval on a central logger using a wireless data transmission technique. These sensors were fixed on a trolley (Figure 1. b) and placed close to the testing area in the classrooms. In addition three thermistor type temperature probes were distributed on a vertical pole fixed to the trolley to record the temperature differences between pupils' head and feet levels. Separate units were placed outdoors and in the corridors to measure CO_2 concentration, temperature and RH. Mass concentration of airborne particles (PM2.5) and noise level were measured during the performance tests on pupils over a few hours. The amount of supplied air to the classrooms was measured with Venturi flow meters built into the duct system downstream of the fan.

Subjective evaluations: Simultaneous to the physical monitoring, measures of self-assessed environmental perception, comfort and health were obtained immediately after the performance tests were carried out. With some exceptions all pupils participated in the testing. The targeted age group of the children was between 9-10 years attending Year 5. This age group of pupils was selected because they remain in their classrooms most of the day and are therefore in the same environment throughout a school day. The pupils were asked to complete a simple questionnaire about the classroom environment, thermal sensation, mood, Sick Building Syndrome (SBS) symptoms and life style, such as hunger and quality of sleep over the previous night believed to affect their performance. The questionnaire about the classroom environment included questions about air stuffiness, dryness, perception of light and noise. The SBS questionnaire focused on symptoms of the mucous membrane and in upper respiratory tract, such as nose congestion, nose, mouth, throat and eye dryness, and neurobehavioral symptoms including headache, attention, dizziness, tiredness, sleepiness. Pupils were asked to rate the intensity of each symptom on Visual Analogue (VA) scales [15]. Thermal sensation was recorded using a 7-point PMV scale [16]. Furthermore, pupils were asked to rate the air movement around their body and inform whether it was acceptable or not.

Pupil's Performance Tests: Two different performance tests were administered to the pupils in each school. Traditional tests were carried out on paper for 40 minutes, including simple addition and subtraction of numbers (15 minutes each) and reading comprehension [17] (10 minutes) similar to that performed in a normal school day. New software (VISCOPE – Ventilation in Schools and Cognitive Performance) was developed that uses algorithms based on the work of Iregren *et al.* [18] to study changes of pupils' cognitive performance under different air quality conditions in classrooms. These tests were conducted on laptop computers set up in the classroom, similar to the method used by Coley and Beisteiner [19]. Both the traditional tests and the computer tests were given to pupils during their lessons preferably before the lunch break when the CO_2 concentrations had reached the maximum level of the morning's teaching session. The computer tests lasted for 20 minutes and were conducted in 3-4 consecutive groups, each group including 7-8 children. The tests, whether they were conducted on paper or computers, were carried out on each testing week on the same weekday and time period for each group of children.

Data analysis: Outdoor air supply rate was calculated based on the mass balance model of CO_2 on each testing day. The subjective and performance data were analysed using Wilcoxon matched-pairs test, using each subject as their own control. All p-values are 1-tailed of an effect in the expected direction.

RESULTS

The current project is still in the phase of data collection hence preliminary results of the physical environment and performance tests conducted on paper from only one school are presented. Detailed analysis of the performance results including those conducted on the computers will be published on the completion of the current investigations.

Figure 2 shows a typical CO_2 pattern in one of the classrooms during a weekday when performance tests were completed. The classroom of 156 m^3 was occupied by 23 children and a teacher at normal activity levels. The teaching schedule including lessons and break time can be clearly followed by looking at the changes in the CO_2 concentrations. The uncontrolled condition on Figure 2 shows the CO_2 level prior to any intervention in the classrooms. The CO_2 concentrations obtained during the week with the re-circulation ventilation are matching closely the uncontrolled levels seen during a normal school day. When the ventilation system was switched on to provide outdoor air the CO_2 concentrations were dramatically reduced and remained below 1000 ppm throughout the school day.

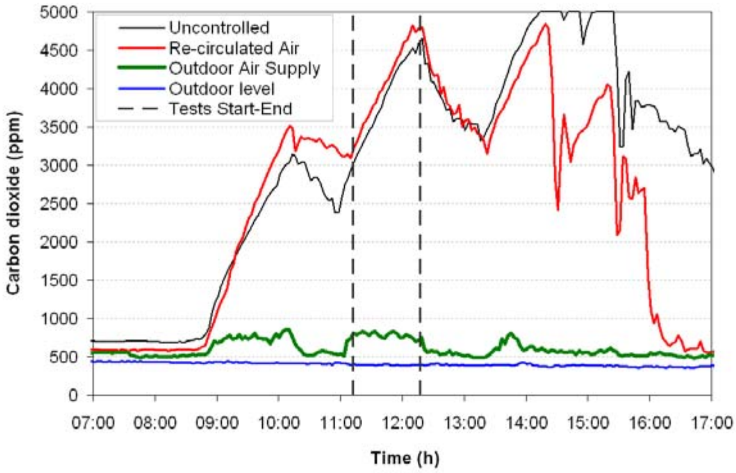

Figure 2. Typical pattern of the CO_2 level inside a classroom at different ventilation conditions on a testing day. The uncontrolled condition reflects CO_2 concentration during a normal school day without any intervention measures.

The average levels of the main physical parameters in the classrooms during the performance tests are presented in Table 1. At low ventilation rates the CO_2 concentrations during the performance tasks at a given day and classroom varied from 1600 ppm up to 4000 ppm depending on the occupancy level prior to testing. Temperature deviations between low and high ventilation rate conditions were within 1.7°C with one exception in classroom B where the difference in the operative temperature reached 2.7°C due to exceptional hot outdoor conditions during the tests conducted on paper. Relative humidity was generally higher at low ventilation rates due to moisture generation from people that is also reflected in the enthalpy of the classroom air. The air exchange rates in the re-circulation mode were not higher than 0.3 h^{-1} in both classrooms, showing an effective building tightness with closed windows that is responsible for the high levels of CO_2 and the extremely low outdoor air infiltration of not more than 0.55 L/s per person. The measured amount of fresh air supplied during improved ventilation was at180 - 190 L/s corresponding to 4.2 - 4.4 h^{-1} air exchange rates. The calculated air exchange based on the CO_2 mass balance model showed higher rates of up to 8 h^{-1} (12 - 16 L/h per person) which is most likely due to some windows being opened that enhanced cross ventilation. The average particle (PM 2.5) concentration during testing was in the range of 0.05 - 0.1 mg/m^3 and did not show major changes due to ventilation improvement. Classroom noise levels during testing were typically between 50 - 70 db(A) depending on the classroom activities. The background noise level originating from the ventilation system installed was less than 48 - 49 db(A).

Table 1. Average levels (± standard deviation) of main environmental parameters inside the classrooms and outdoors during performance testing; the ventilation rate calculation is based on the CO_2 mass balance model for each classroom; outdoor CO_2 level was at 380-420 ppm.

	class room	Testing on Computer		Pen & Paper testing	
		Re-circulated Air	Oudoor Air Supply	Re-circulated Air	Oudoor Air Supply
CO_2 level [ppm]	A	2876 ± 446	735 ± 58	1638 ± 364	709 ± 30
	B	4093 ± 509	783 ± 35	2086 ± 171	593 ± 7
Air temperature [°C]	A	20.5 ± 0.3	18.9 ± 0.2	20.9 ± 0.3	20.1 ± 0.2
	B	18.7 ± 0.4	20.3 ± 0.7	18.4 ± 0.4	21.5 ± 0.5
Relative Humidity [%]	A	67 ± 1	56 ± 2	69 ± 1	52 ± 1
	B	66 ± 1	55 ± 3	61 ± 1	64 ± 2
Operative temperature [°C]	A	20.5 ± 0.4	18.8 ± 0.3	21.1 ± 0.4	20.2 ± 0.2
	B	19.0 ± 0.5	20.2 ± 0.7	18.9 ± 0.4	21.6 ± 0.5
Outdoor temperature [°C]	A	16.9 ± 0.5	17.7 ± 0.5	24.9 ± 0.5	17.9 ± 0.1
	B	16.7 ± 4.5	21.2 ± 0.9	17.8 ± 0.2	25.0 ± 0.5
Enthalpy [kJ/kg]	A	46.41	38.41	48.28	39.64
	B	41.45	41.24	39.00	47.85
Ventilation Rate	A	0.55	16.0	0.51	14.8
[L/s.person]	B	0.36	13.9	0.20	12.2

Table 2. Results of a selection of subjective votes recorded following the performance tests; significance of statistical tests also appear next to each question; n.s.= not significant.

Perception / Symptom / Comfort	classroom	Testing on Computer			Pen & Paper testing		
		Re-circulated Air	Oudoor Air Supply	p <	Re-circulated Air	Oudoor Air Supply	p <
Air Stuffy (0) -	A	48	81	0.01	34	72	0.01
Fresh (100)	B	71	66	n.s.	66	52	n.s.
classroom Noisy (0) -	A	62	91	0.01	66	87	0.01
Quiet (100)	B	51	59	0.05	81	80	n.s.
Dreamy (0) -	A	57	61	n.s.	52	63	0.08
Attentive (100)	B	70	72	n.s.	59	61	n.s.
Tired (0) -	A	57	59	n.s.	39	50	0.10
Not Tired (100)	B	57	58	n.s.	61	57	n.s.
Sleepy (0) -	A	57	61	n.s.	40	63	0.01
Alert (100)	B	68	69	n.s.	63	60	n.s.
Feel like Working (0) - Do	A	46	56	n.s.	27	41	0.01
not feel like working (100)	B	68	68	n.s.	62	60	n.s.
Thermal Comfort (-3 =	A	1.1	0.3	0.02	1.8	0.2	0.01
Cold, +3 = Hot)	B	0.4	0.9	n.s.	0.1	0.9	0.01
classroom environment	A	60	77	0.04	56	69	0.03
Bad (0) – Good (100)	B	80	83	n.s.	78	81	n.s.

Selected results of subjective responses to the classroom environment immediately after testing are included in Table 2. The pupils in classroom A perceived the air as being fresher, the classroom less noisy and their general feeling about the classroom environment was significantly better in the condition with increased ventilation compared to that with re-circulation. There was a trend approaching significance towards higher alertness, better work mood and tendency for less tiredness and increased attention following the performance tests conducted on paper at the higher ventilation rates. The pupils' thermal sensation was in accordance with the existing temperature differences shown between the conditions. They were closer to neutral at operative temperatures between 18.8 and 20.2 °C and felt slightly warm at 20.5-21.6 °C.

Evaluation of the reading comprehension task was made according to the marking sheet provided with the tasks. Compared to a maximum mark of 16, the children in classroom A obtained an average mark of 9.4 in the condition with improved ventilation that showed a tendency of a higher rating ($p<0.09$) than 8.1 achieved in the other condition with low outdoor air supply rate. No significant change was found in the reading comprehension marks of children from classroom B between the two experimental conditions. Details of the maths based performance measures for all (40) children who completed the performance tasks in both experimental condition are shown in Table 3.

Table 3. Average speed, accuracy and overall performance (i.e. number of error-free units) of subjects achieved in the addition and subtraction tasks.

Class-room	Condition	Addition task			Subtraction task		
		Speed (units/h)	Error Rate (%)	Performance (units/h)	Speed (units/h)	Error Rate (%)	Performance (units/h)
A	Re-circulated Air	142.3	23%	111.2	149.1	43%	90.1
	Outdoor Air Supply	143.0	19%	118.7	142.7	37%	90.9
B	Re-circulated Air	139.2	15%	121.3	144.4	28%	103.4
	Outdoor Air Supply	144.4	13%	125.5	143.4	21%	114.3
A + B	Re-circulated Air	140.8	19%	116.0	146.9	36%	96.4
	Outdoor Air Supply	143.7	16%	121.9	143.0	30%	102.0

The children in classroom A tended to work more accurately in both addition ($p<0.07$) and subtraction ($p<0.07$) tasks and slight improvement in the overall performance of addition ($p<0.068$) was noticed at the higher ventilation rate compared to low ventilation. Similarly, the pupils in classroom B made significantly less errors ($p<0.01$) and achieved better performance ($p<0.029$) during subtraction at the higher ventilation rate. For classroom B the changes in the performance measures of addition did not reach significance levels. However, when the data for classroom A and B were pooled under the common hypothesis that the children work better under improved ventilation, significant or close to significant improvement was obtained in the overall performance of both addition ($p<0.036$) and subtraction ($p<0.052$). Separate analysis was carried out for children with higher math skills (25 pupils for both classrooms), i.e. excluding those who had a higher than 50% error rate in these tasks. This analysis resulted in similar but more significant effects than those for individual classrooms above. The children with higher math skills increased the number of error-free units in both addition ($p<0.02$) and subtraction ($p<0.007$) tasks when working under the improved ventilation conditions.

DISCUSSION

The CO_2 patterns over a school day are closely linked to the daily activities performed within or away from the classrooms and whether windows and doors are left open or not. The levels presented in Figure 2 reflect a situation when the classroom was occupied throughout a full school day and no windows were opened due to cool outdoor conditions without sunshine. Double glazed windows, installed at the majority of the schools studied, allow very little air infiltration. If windows are left closed in the absence of other means of providing a minimum amount of outdoor air CO_2 levels rise quickly (typically within 15-20 minutes) to 3000-4000 ppm under normal occupancy. Similar high levels in naturally ventilated classrooms have often been reported in UK schools [6], [10]. Adverse health effects associated with CO_2

exposure below 5000 ppm are difficult to evaluate since there are a number of other factors such as high pollution level from off gassing of building materials and elevated allergen concentration, appearing at low ventilation rates that also affect human wellbeing [20]. However, possible alteration in breathing and heart rate as well as loss of concentration and wellbeing due to CO_2 exposures in the range between 3000-5000 ppm may be expected [21]. Other adverse health effects due to CO_2 exposure such as dyspnea, headache, dizziness and lethargy were found mainly in medical investigations and short term exposures to CO_2 concentrations above 1% (10000 ppm) [22].
The thermal conditions during the first testing week were generally cooler both indoors and outdoors compared to the second week of testing. Therefore the average temperatures were somewhat higher under the re-circulated condition in classroom A and under improved ventilation in classroom B. Considering that the thermal environment may also affect work performance [11] the thermal conditions in classroom A would be in favour, and in classroom B would counteract the expected changes in performance due to improved ventilation. However, the alterations in temperature between the present experimental conditions were relatively small compared to those in which such effect were shown [11] and therefore these may be considered not to affect the present performance results. On the other hand the thermal conditions in classroom B have to some extent affected the pupils' perception in air freshness. Although the air quality conditions were improved the pupils did not perceive significant improvement in air freshness mostly due to the increased enthalpy of inhaled air at high ventilation [23]. The children in classroom A who effectively perceived a change in air freshness under improved ventilation also reported more positive effects in neurobehavioral symptoms (alertness, attention, tiredness) and work mood in contrast with children in classroom B.
A significant impact of the ventilation rate on the school work performance of pupils was observed in both classrooms. Summarizing the effects the overall performance of all children increased under improved ventilation by 5.1% and 5.8% for both addition and subtraction respectively. These effects were even stronger for the pupils with higher math skills. They increased their math performance by ~7% when working under the improved ventilation conditions. The magnitude of such effect is in the expected range that was seen in earlier studies investigating work performance due to improved ventilation rates [7], [11].

The present results strengthen the evidence of earlier findings that improved ventilation has beneficial effect on pupils' learning performance. Without intervention the existing ventilation rates in naturally ventilated school buildings remain below the minimum recommended levels if thermal conditions do not influence people to open windows. Measures that allow a minimum supply of fresh air to the classrooms of naturally ventilated buildings are needed particularly if windows are not operated adequately to control ventilation.

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