Final Report

Project title:
Energy-efficient window opening for temperature and air quality control in school classrooms

Institution:
DTU Civil Engineering, Building 402, 2800 Kgs. Lyngby

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Technical Report

All experimental activities were completed. Two manuscripts were prepared based on the measurements carried out in schools:

- Use of visual CO2 feedback as a retrofit solution for improving classroom air quality by Wargocki and Silva submitted to Indoor Air Journal

- Ventilation System Type, Classroom Environmental Quality and Pupils' Perceptions and Symptoms by Gao, Wargocki and Wang submitted to Building and Environment

The copies of the manuscripts are attached to this report.

Financial report

The project financial statements were reviewed and the project account was closed. The final financial report is attached.

Status projekt 26149 til dato (2011-01 til 2013-11)

UK	Top opgave	Opgave	Budget hele projektet	Forbrug til valgt dato	Rest	Budget timer hele projektet	Forbrug timer til valgt dato	Rest timer
95	X	X-01 - VIP løn	220.088,34	190.969,53	29.118,81	521,8	458,8	63,0
		X-12 - Materialer	4.999,99	3.198,99	1.801,00	0,0	0,0	0,0
		X-13 - Øvrig drift	108.082,07	105.335,57	2.746,50	0,0	0,0	0,0
		X-99 - Lukning	0,00	33.829,23	-33.829,23	0,0	0,0	0,0
		X-Overhead - UK95-Overhead	66.634,09	66.666,68	-32,59	0,0	0,0	0,0
		Total	**399.804,49**	**400.000,00**	**-195,51**	**521,8**	**458,8**	**63,0**
	Total		**399.804,49**	**400.000,00**	**-195,51**	**521,8**	**458,8**	**63,0**
Total			**399.804,49**	**400.000,00**	**-195,51**	**521,8**	**458,8**	**63,0**

Use of visual CO_2 feedback as a retrofit solution for improving classroom air quality

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ABSTRACT

Carbon dioxide (CO_2) sensors that provide a visual indication were installed in classrooms during normal school operation. During two-week periods, teachers and students were instructed to open the windows in response to the visual CO_2 feedback in one week and open them as they would normally do, without visual feedback, in the other week. In the heating season, two pairs of classrooms were monitored, one pair naturally and the other pair mechanically ventilated. In the cooling season, two pairs of naturally ventilated classrooms were monitored, one pair with split cooling in operation and the other pair with no cooling. Providing visual CO_2 feedback reduced CO_2 levels, as more windows were opened in this condition. This increased energy use for heating and reduced the cooling requirement in summer. Split-cooling reduced the frequency of window opening when no visual CO_2 feedback was present, suggesting that classroom temperature is the driving factor for this behavioural response. The children liked visual CO_2 feedback: it can thus be used as a valuable warning signal for poor air quality in classrooms with mechanical cooling, and, in climates with mild winters, to ensure adequate ventilation until heat recovery solutions are available.

KEYWORDS

Schools; Classrooms; Carbon dioxide; Ventilation; Retrofit solution; Energy; Indoor Air

Quality

PRACTICAL IMPLICATIONS

Visual CO_2 feedback can be installed as an interim solution that improves air quality in room volumes that can be aired out only if the occupants open the windows, although this will increase energy use for heating in cold climates. Visual CO_2 feedback can also be used as a permanent solution that will ensure adequate outdoor air supply rates in buildings with mechanical cooling, where windows are normally kept closed to save energy. When building occupants are accustomed to open windows, they will do so independently of the indoor air quality and more often in response to increased indoor temperatures. Energy simulation tools should therefore include by default a basic level of window opening, or energy use will be underestimated.

INTRODUCTION

Many studies have found that the environmental conditions in elementary schools are inadequate. The most common problems in schools are insufficient outdoor air supplied to occupied volumes; elevated and varying temperatures; water leaks; inadequate exhaust air flows; poor air distribution or balance; and poor maintenance of heating, ventilation and air-conditioning systems (Daisey et al., 2003). The likely reasons for this situation are inadequate financial resources for the maintenance and upgrade of school buildings, and an overemphasis on energy conservation that gives rise to conditions that are worse than what is stipulated by the relevant standards and building codes. Thus classroom temperatures are allowed to drift above the recommended range of 20-22^{o}C in warm weather and outdoor air supply rates are allowed to remain so low that carbon dioxide (CO_2) levels regularly exceed 1,000 ppm during school hours. A recent review of the literature by Santamouris et al. (2008) found that the median CO_2 concentration in classrooms that were naturally ventilated was 1,410 ppm while field measurements in Denmark found that more than half of the 743 classrooms in which the measurements were carried out had CO_2 levels above 1,000 ppm (Wyon et al., 2010).

Children are quite vulnerable and more susceptible to environmental impacts than healthy adults (Landrigan, 1998). They spend more than 30% of their waking hours in classrooms. They must attend schools even when the air quality and thermal conditions in the classrooms are unsuitable, because it is obligatory to take part in elementary education. Elevated classroom temperatures and poor ventilation can negatively affect the learning process by reducing the performance of typical schoolwork and the academic achievements of children and by increasing absenteeism (Haverinen-Shaughnessy et al., 2010; Shendell et al., 2004; Bako-Biro et al., 2012; Mendell et al., 2013; Wargocki and Wyon, 2013). It is therefore essential that environmental conditions in classrooms should be such that they promote rather than hinder learning to avoid negative consequences for the proper development of young people, and an increase in societal and economic costs (Chetty et al., 2010; Slotsholm, 2012).

Many existing schools are naturally ventilated, i.e. the classrooms can be aired out only if the pupils and teachers open the windows. These schools would have to be retrofitted with systems that ensure adequate air quality and temperature if they are to ensure improved indoor environmental quality in classrooms at all times. These systems may use either natural or mechanical forces, but in either case, the retrofit may be quite expensive. The expense is due not only to the potentially high first costs but also to the increased energy and maintenance costs that are incurred when systems that ensure high classroom quality are in operation. Retrofitting the existing building stock may take many years to complete. It can also disturb teaching, unless it is carried out during school vacations. Simple retrofit solutions are therefore needed as an interim measure. These solutions should be easy and quick to implement, they should preferably require no radical changes to the existing building structure and cause no disruption of teaching procedures, they should be relatively cheap and they should be energy efficient.

The present study examined one such solution: an apparatus providing a visual feedback signal to pupils that indicates the current CO_2 level in the classroom, indicating when the windows in the classroom should be opened so that the classrooms can be properly aired out, and when they can be closed to conserve energy. The goal was to determine whether opening windows in classrooms in response to visual CO_2 feedback would improve the outdoor air supply rate as indicated by CO_2 levels, the effects of this on classroom temperatures, the perceptions and symptoms reported by pupils and the effects on energy use.

METHODS

Field experiments were carried out in pairs of identical classrooms in an elementary public school in a small coastal town located about 30 km north of Copenhagen. The experiments were carried out during normal school operation in the 4th, the 6th and the 8th grade classrooms. There were on average 23-24 pupils in each class.

The classrooms had large glazed south-facing facades with operable windows. Each classroom had a floor area of 50 m^2 plus 15 m^2 of entrance hall and a total volume of 187.5 m^3. The classrooms were heated by water-filled radiators with thermostatic valves, located under the windows.

The classrooms were normally ventilated by mechanical ventilation systems; the air handling units included heat recovery and preheating of the supplied air, and each served 2 to 4 classrooms. They were installed in the cellar under the classrooms they served. The outdoor air supply rates in the 4th to 6th grade classrooms have previously been estimated at about 3 to 4 L/s per person (Wargocki and Wyon, 2013), while the air supply rates in the 7th to 9th grade classrooms were controlled by a sensor to ensure that carbon dioxide levels were not higher than 1,000 ppm. Pilot measurements were performed a few weeks prior to the experiments and confirmed that the 4^{th} and 6^{th} grade classrooms must have had lower ventilation rates than indicated above, because the peak measured CO_2 concentrations reached levels above 1,500 ppm.

The classrooms could be additionally aired out by teachers and students by opening any of the five operable windows; if the main doors facing the corridor were also opened, cross-ventilation could be achieved.

Two of the classrooms were also equipped with split-cooling units with barely-audible air-circulation fans. These units had been installed for a previous field experiment that was carried out in this school (Wargocki and Wyon, 2013). No additional supply air is provided by split-cooling units: they cool room air and dissipate the heat outside the building. The units were operated only occasionally during the school year, if the outdoor temperatures were much higher than usual in the late spring or late summer.

In a week prior to and during experiments, the systems in the 4th and 6th grade classrooms were idled to create the condition in which the classrooms could only be ventilated by opening windows. Since the classrooms already had very low ventilation rates, as indicated by the pilot measurements, idling the system was not expected to substantially aggravate the conditions in the classrooms. Idling of the system can be regarded as simulating either failure of the normal operation of the ventilation system or its regular maintenance break during the school year, both being quite likely to occur.

CO_2 sensors that provide a green/yellow/red continuous visual indication of CO_2 levels in the range from 400 to 2,000 ppm in steps of 200 ppm were installed in classrooms, to indicate to the teachers and students when the windows should be opened and when they could be closed (Figure 1). Green diodes indicated CO_2 levels below 1,000 ppm, yellow in the range from 1,000 to 1,600 ppm and red the levels above 1,600 ppm; the higher the CO_2 levels the more diodes were lit. The teachers and students were instructed to open the windows proportionally in response to the visual feedback. This means that not all the windows were opened at once: they were opened one by one, as an increasing number of yellow lights were lit. When the lights were red, the pupils and teachers were instructed to open all windows and the main door to achieve intensive cross-ventilation. They should then leave the classroom for a short while to allow the CO_2 level to drop. No other feedback was provided to pupils and teachers, e.g. neither the classroom temperature nor the outdoor temperature, nor the condition imposed.

Insert Figure 1 here

The experiments were carried out during two-week periods in the heating season (March-April 2011) and the cooling season (June 2011). During the heating season, two pairs of classrooms were selected, one pair in which the ventilation system was idled and the classrooms could be aired out only by opening the windows (4th grade classrooms), and one pair with the mechanical ventilation system, which was controlled by a separate sensor to keep classroom CO_2 below 1,000 ppm, in operation (8th grade classrooms). The visual feedback was installed in one of the classrooms in each pair for one week, then moved to the other classroom in the pair, in a crossover design that is capable of balancing any effects of order of presentation and is robust to changes in external factors such as weather. Visual feedback was also installed in classrooms in which the mechanical ventilation system was in operation, to determine whether the windows were opened by pupils even though the visual feedback did not indicate that they should do so. During the non-heating (cooling) season, two pairs of classrooms in which the ventilation system was idled were examined, one pair with split cooling (4th grade classroom) and another pair with no cooling (6th grade classroom); visual feedback was installed in one of the classrooms with cooling and in one of the classrooms with no cooling. A cross-over design was not applied, so each of these 4 classrooms either had no visual feedback or had visual feedback for both experimental weeks. This made it possible to examine window opening behaviour over two school weeks. The thermostatic control of the split-cooling units, when in operation, was set to 22°C.

During the experiments, no changes to teaching schedules or normal school activities were made, to ensure that the teaching environment and routines were as normal as possible. During the weeks when no visual feedback was provided, the teachers and pupils were asked to open the windows as they normally would have done and no restrictions on window opening behaviour were imposed.

The classroom CO_2, temperature and relative humidity were continuously monitored during the experiments with a calibrated Vaisala GM20D sensor for CO_2 (accuracy: ±30ppm + 2% of the reading) connected to a Hobo U12 logger monitoring temperature and relative humidity (accuracy of ±0.7°C and ±5% RH, respectively). A weather station (PCE FWS 20 Weather Center) was located on the roof for continuous logging of outdoor conditions (temperature, relative humidity, wind direction and wind speed). Miniature event loggers (Hobo State) with magnetic sensors were attached to the window and door frames; the loggers recorded when each window/door were opened and for how long. Only the data from the periods when pupils were present in the classrooms were used in the subsequent analyses.

Energy use was monitored during the 2 weeks of measurements in the heating season by installing electronic metering devices (Brunata Futura+) for recording the heat dissipated by the water-filled radiators. The thermostatic valve settings remained unchanged during these measurements. The monitoring period was too short for it to be reasonable to extrapolate the results to the entire school year. Instead, they were used to calibrate a simulation of annual energy use in different classrooms: the relative difference in predicted energy use for heating between the classrooms was constrained to match the energy use measured by the meters installed on the radiators in the classrooms during the measurements.

Modelling of annual energy use was performed using IDA-ICE 4. Some modelling assumptions in IDA-ICE 4 were standardised in order to facilitate comparison between ventilation types. The window opening was simulated assuming that they were opened according to the visual feedback, or that they were opened according to CO_2 levels measured in the classrooms (the windows were not assumed to be open until the CO_2 level was higher than 1,400 ppm) and to maintain the set points for classroom temperature (windows were also assumed to be open when temperatures were too high and closed when they were too low). It was decided to introduce control by CO_2 levels in simulations of the case when visual feedback was not installed, to avoid instances in which windows would not be opened at all (which seldom occurs, as argued below, Fig. 3) especially in winter when window opening depends only on the indoor temperature. It was assumed that the outdoor air supply rate in the mechanically ventilated classrooms was 300 m^3/h and that the efficiency of the heat recovery system was 70%; the models were run with the lighting/equipment systems consuming the same energy in all classrooms. The data on heat transmission coefficients were estimated using blue-prints of the classrooms. A standard nine-month school year was used in the analyses and the schedules for the ventilation system, heating system, lighting and occupancy were those actually used in the school where the measurements were carried out. The school was assumed to be unoccupied during the weekends. The analyses used a standard ASHRAE weather file for the climate zone of Copenhagen, Denmark. Because of the simplified nature of the above assumptions, only a relative comparison in annual energy use between different simulated scenarios is reported here.

On Thursday of each week, towards the end of the school day, children rated the indoor environment and the acute health symptoms they experienced at the time of completing the questionnaire. The following perceptions and symptoms were rated, using a paper questionnaire that was distributed by the teachers: quality of the classroom environment, thermal environment, classroom air quality, air movement, the acoustic environment in the classroom, air humidity and illumination, ability to breathe, fatigue, headache, willingness to learn, dryness of lips, skin and throat, and general mood (Table 1). They were rated on a visual-analogue scale where the line was replaced by a set of “smiley’s” to make it easier for children to indicate their response (Figure 2). The children were also asked to rate whether they liked or disliked the visual CO_2 feedback display; they used the scale shown in Figure 1 to indicate their response.

The within-subject responses collected in the heating season were analysed using the Wilcoxon Matched-Pairs Signed Ranks test. In the cooling season, the responses of different children in two different classes were compared using the Mann-Whitney U test.

Insert Figure 2 here

RESULTS

Figure 3 shows how providing visual CO_2 feedback affected the opening of windows and the conditions in the classrooms during experiments performed in the heating season (winter) and the non-heating season (late spring/early summer). Outdoor temperatures during the experiments are also shown.

Insert Figure 3 here

During the two weeks of experiments in the heating season (winter), with outdoor temperatures during school hours of 6 to 12^{o}C, children opened the windows more frequently when the visual feedback was present in classrooms with no mechanical ventilation system in operation (1st column of Figure 3). As a result, the CO_2 levels in these classrooms were at or below 1,000 ppm, the level at which children were instructed to open the windows. The CO_2

levels without visual feedback were as high as 1,400 to 1,800 ppm, close to the levels registered during the pilot measurements. In the classrooms with a mechanical ventilation system in operation, the CO_2 levels remained below 1,000 ppm, and there was some basic level of window opening whether the visual feedback was present or absent (2nd column of Fig. 3). Classroom temperatures were not affected by more frequent opening of windows and they were slightly lower in the classrooms with no mechanical ventilation in operation. In the latter classrooms the temperature increased by nearly 3°C in the first hour of a school day, after which it remained constant at about 21°C. In classrooms with mechanical ventilation, the temperature increased during the day by about 1.5-2°C, reaching about 23°C towards the end of each school day.

During two weeks of experiments in the non-heating (cooling) season (late spring/early summer), the outdoor temperatures during school hours were in the range 18 to 22°C. There was no difference in window opening behaviour when visual feedback was provided in the classrooms without cooling, except for the early morning hours when the CO_2 levels in the classrooms without visual feedback were slightly elevated (3rd column of Fig. 3). As the temperature increased during each day, more and more windows were opened in this classroom and CO_2 levels dropped below 1,000 ppm. This did not have much effect on classroom temperatures, which continued to rise throughout school hours and reached 23-25°C. In the classrooms in which cooling was installed the temperatures were maintained fairly constant at 22-23^{o}C independently of whether visual CO_2 feedback was present or not (4th column of Fig. 2), i.e. close to the set point of the split unit. However, in these classrooms the windows were opened less frequently when there was no visual feedback, leading to slightly elevated CO_2 levels of about 1,200 ppm. The only parameter that changed noticeably during the experiments was the level of CO_2 (when no visual feedback was provided) as occurred in classrooms without mechanical ventilation in winter. In the classrooms with no cooling in late spring/early summer, on the other hand, the difference in conditions between the classrooms with and without visual feedback appeared to be mainly due to the difference in temperature, though to some extent also to CO_2 levels in the early part of the school day. No effect of visual feedback on conditions was observed in the mechanically ventilated classrooms in winter (Figure 3).

Children liked the visual CO_2 feedback, both as reported using the scale with smiley's (Figure 4) and in their written comments.

Insert Figure 4 here

Installing visual CO_2 feedback and the changes this caused in classroom conditions had some effect on the perceptions and symptoms indicated by pupils (Table 1). In winter, in classrooms where the mechanical ventilation system was not operating and the visual feedback was installed, children felt significantly better, reported significantly less dry throat and indicated that they were significantly more willing to work compared with the classroom without visual feedback. In classrooms where the mechanical system was in operation, many perceptions and symptoms differed between the weeks with the visual feedback absent and present: with the visual CO_2 feedback, pupils felt better, the air was perceived to be fresher, pupils had fewer problems with breathing, they were less tired and had less severe headaches, and less dry lips and throat; all of these differences reached statistical significance ($P<0.05$) or approached significance ($P=0.06$), Table 1. In late spring/early summer, there were no differences in perceptions and symptoms between classrooms with and without the visual feedback where there was no cooling. In classrooms with cooling, all perceptions but one (light intensity) were significantly different in the classroom with the visual CO_2 feedback: they reported that it felt colder, the air was fresher and more still, it was more noisy and more humid. Additionally, the children reported that they could breathe more freely, had less severe headaches, and were more willing to work in this classroom, all differences reaching statistical significance ($P<0.05$) or approaching significance ($P=0.06$), Table 1.

Insert Table 1 here

Simulations of energy use showed that the estimated annual heating demand was on average 15-23% higher and the annual cooling demand 18% lower in classrooms with visual CO_2

feedback compared to classrooms without visual CO_2 feedback (Table 2).

Insert Table 2 here

DISCUSSION

As expected, providing pupils with a visual signal that indicated when the windows should be opened and when they could be closed reduced the observed CO_2 concentration and improved classroom air quality. The average CO_2 levels in the classrooms with visual CO_2 feedback were at or below 1,000 ppm and thus met the design criteria recommended by the Danish Working Environment Authority [arbejdstilsynet.dk] and the Danish Building Regulation (2010); overall, the average CO_2 concentrations were not higher than 2,000 ppm, which is an action level indicating the need for improving indoor climate conditions [arbejdstilsynet.dk]. Although the outdoor air supply rates were not estimated in the present experiments, if the children are assumed to be moderately active, the measured levels of CO_2 in classrooms with visual feedback suggest that they exceeded 6 L/s per person, and thus complied with the Danish Building Regulations (2010). The present results were all obtained in one school, located in a rural area with good ambient air quality (although no actual data for ambient air quality was available), so it may be inadvisable to generalise these results to urban schools with noisy ambient environments and polluted ambient air. However, it is worth noting that similarly reduced classroom CO_2 levels were obtained in a large number of Dutch schools when visual CO_2 indicators were installed (Geelen et al., 2008). The experiments in the heating season were performed in periods with quite mild ambient temperatures. This meant that classroom temperatures were not affected when windows were open and the pupils did not complain of cold drafts or fluctuating temperatures. This may not be the case when outdoor temperatures are lower than those in the present experiments and therefore the results should not be generalised to colder outdoor conditions until more evidence is available.

Although installing visual CO_2 feedback would improve classroom ventilation in the heating season, as indicated by reduced CO_2 levels, it would also increase energy use, as shown by the energy simulations, because the volume of outdoor air that must be heated is higher. This is an inevitable trade-off when using visual CO_2 feedback in temperate and cold climates, unless some of the energy that is used to heat the additional outside air that enters the classroom when visual CO_2 feedback is installed can be recovered. This should be considered as an important limitation on the use of this solution. Visual CO_2 feedback alone should probably be considered only as an intermediate and temporary solution for improving classroom ventilation in temperate and cold climate zones.

In classrooms with cooling, windows were opened less frequently when no visual CO_2 feedback was provided. This indicates that pupils open the windows in response to elevated classroom temperature rather than because the air quality is poor, as was suggested by Wyon and Wargocki (2008) on the basis of their experimental data; Fabi et al. (2013) also found that temperature is an important factor that determines whether windows are opened or closed. This is consistent with what was observed in classrooms without cooling, where windows were opened just as frequently whether visual CO_2 feedback was present or not. The visual CO_2 feedback thus appears to be a very useful warning system in classrooms where mechanical cooling is applied. It would be very beneficial in areas where high outdoor temperatures necessitate the use of mechanical cooling (air conditioning) in schools and where the use of air conditioning is increasing.

The energy simulations showed that installing visual CO_2 feedback would reduce the cooling requirement in the cooling season because it leads to more frequent window opening; these results are valid for climates similar to that of Denmark, as assumed in the simulations. The net effect on annual energy use was small, as the cooling requirement was less than 5% of the energy required for heating, i.e. heating accounts for most energy use in the type of climate for which the simulations were performed. Simulations for other climates are required.

Using visual CO_2 feedback when outdoor temperatures are high may not be sufficient to reduce the thermal discomfort of pupils. This may have consequences for learning (Wargocki and Wyon, 2013) and for the performance of teachers (Lan et al., 2011). The indoor temperatures measured in the present experiments in the cooling season, in the classrooms without cooling, are shown on the graph defining the adaptive thermal comfort model relating acceptable operative temperatures indoors to outdoor temperatures (Figure 5) (EN15251, 2007). In most cases, the measured classroom temperatures were within the range specified by the model as Class I , corresponding to less than 10% dissatisfied, Class II (less than 20%) and Class III (less than 35%). Nevertheless, Table 1 shows that pupils indicated that it was significantly warmer in the classroom without visual CO_2 feedback, although the temperature in this classroom was only about 2^{o}C higher (Figure 2). The pupils were not asked whether the warmer temperatures would be acceptable but it is likely that it was the slightly raised temperature that caused the air to be perceived as significantly less fresh and the environment in the classroom to be considered poorer (Table 1). This indicates that there were negative effects and that the pupils were aware of them.

Insert Figure 5 here

It is interesting to note that in the classrooms with mechanical ventilation the pupils opened the windows even when the visual CO_2 feedback showed that CO_2 levels were below 1,000 ppm. This indicates that windows may be opened even when the classroom conditions are judged to be acceptable, and that this behavioral response is customary. Future energy simulation programs should probably assume a default minimum (basic) level of window opening. This will lead to energy use being predicted better than it has been to date (Fabi et al., 2013). A basic level of window opening was not assumed in the present simulations: it was assumed that windows would always be closed when CO_2 levels were below 1,000 ppm, although Figure 2 shows that this was not the case.

Generally, the symptoms reported by the pupils had low intensity; the intensity was between 4 and 7 on the 7-point scale, where 1 indicates high intensity and 7 indicates low intensity/no symptoms (Figure 1 and Table 1). The intensity of a number of symptoms was significantly lower in the condition when visual CO_2 feedback was installed in classrooms, but it is not possible to know whether these effects can be attributed to the presence of visual CO_2 feedback or to the improved classroom conditions that resulted from it. A crucial example is the classroom with mechanical ventilation: there were no measurable differences between the temperatures and CO_2 levels in that classroom with and without visual CO_2 feedback, but the intensity of several symptoms was lower when visual CO_2 feedback was provided. In addition, pupils in this condition reported that it was significantly better and that the air was fresher. This difference cannot be attributed to any change in the conditions in the classrooms. It is also unlikely that external factors such as outdoor air pollution could cause the difference since a cross-over design was used to control for this and other potentially disturbing external factors. It is therefore likely that these differences had a psychological origin: pupils were expecting that the use of visual CO_2 feedback would improve classroom conditions, and so indicated lower symptom intensity.

No differences in perception were found in the classrooms with no mechanical ventilation, with and without visual CO_2 feedback, although there was a significant difference between measured CO_2 levels. This was unexpected, as several published reviews have shown that a difference in CO_2 levels (which is usually an indicator of a difference in air quality) do result in measurable effects on symptoms, though predominantly for adults (Apte et al., 2000; Seppanen et al., 1999; Wargocki et al., 2002). No clear differences in symptoms, especially when the measured classroom conditions were changed, is in agreement with previously reported experiments (Wargocki and Wyon, 2013), where the perceptions and symptoms of pupils were also hardly affected by the improved air quality even when their performance of schoolwork was markedly improved. The only exception was the perceptions and symptoms in classrooms with no cooling in late spring/early summer. Higher measured temperatures in classroom without visual CO_2 feedback were reported by pupils and consequently many symptoms were reported to have a higher intensity in this condition. Generally, a lack of differences in perceptions and symptoms may be because children in elementary schools, especially at the age of 12 years old and below, may have difficulty in interpreting the scales. In the present experiments, “smileys” instead of the linear scale were used but even this did not always lead to an effect on perceptions and symptoms. Larger groups of children may be required when working with this age group.

It would be advisable to examine whether providing a visual feedback signal causes sufficient distraction from schoolwork to have a negative effect on school performance and teaching, and whether children continue to open the windows using the feedback beyond the two week periods studied in the present experiments.

CONCLUSIONS

Visual CO_2 feedback can improve the air quality in classrooms but at the same time will increase energy requirement in schools located in temperate and cold climates where heating accounts for most energy use. Despite this limitation, the use of CO_2 feedback may be recommended as a feasible solution for controlling classroom air quality in rural schools with natural ventilation when ambient climate conditions are mild, especially in winter, when the ambient air pollution is low and when the ambient noise levels are low.

Classroom temperature seems to be the main factor affecting window opening. Mechanical cooling of naturally ventilated classrooms may be counter-productive, as it will have a negative effect on this behavioural response and may result in poor classroom air quality. Visual CO_2 feedback can play an important role in such cases, especially in climates where air conditioning is very common, as it can provide a warning signal that the air quality has deteriorated. This is true not only for classrooms in schools but also for other building types, especially residential buildings, including bedrooms and children's rooms.

Windows were opened even when the visual CO_2 feedback did not indicate the need for it, suggesting that habits and customs are to some extent responsible for this behavioural response. Future energy simulation software can improve their predictions by assuming that a basic minimum level of window will occur independently of indoor/outdoor conditions. More data on this would therefore be useful.

ACKNOWLEDGEMENTS

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Figure captions:

Figure 1. Apparatus providing the visual CO_2 feedback used in the present experiments

Figure 2. An example of a scale used to obtain the perceptions and symptoms of pupils. The scale was scored as follows: A=7, B=6, C=5, D=4, E=3, F=2 and G=1.

Figure 3. Time-weighted averages of the percentage of windows opened (100% means that all windows were opened), of the measured classroom CO_2 concentrations and the classroom temperatures during school hours with and without visual CO_2 feedback; the last row shows the time-weighted average values of the outdoor temperatures registered during the experiments in winter (heating season) and in late spring/early summer (non-heating season); only the periods during school hours (8:00 to 15:00) are shown

Figure 4. Evaluation of the visual feedback by pupils in winter and late spring/early summer; A indicates that it was liked very much by the pupils and G that it was not liked at all

Figure 5. Measured air temperatures in the classroom with no cooling outside the heating season (late spring/early summer) superimposed on the relationship between the operative temperature and the mean monthly outdoor temperature defining the adaptive thermal comfort model

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Table 1. Perceptions and symptoms indicated by pupils on the scale illustrated in Figure 1 Medians [25th percentile -75th percentile]; P-values show whether the differences between classrooms with and without visual CO2 feedback were significant

Table 2. Simulated (IDA-ICE 4) annual energy demand [kWh] for heating and cooling in classrooms with and without visual CO_2 feedback

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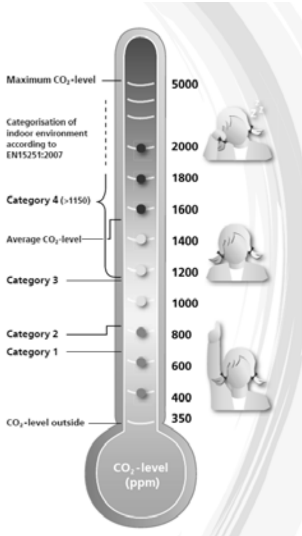

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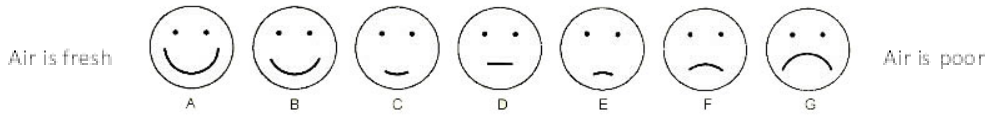

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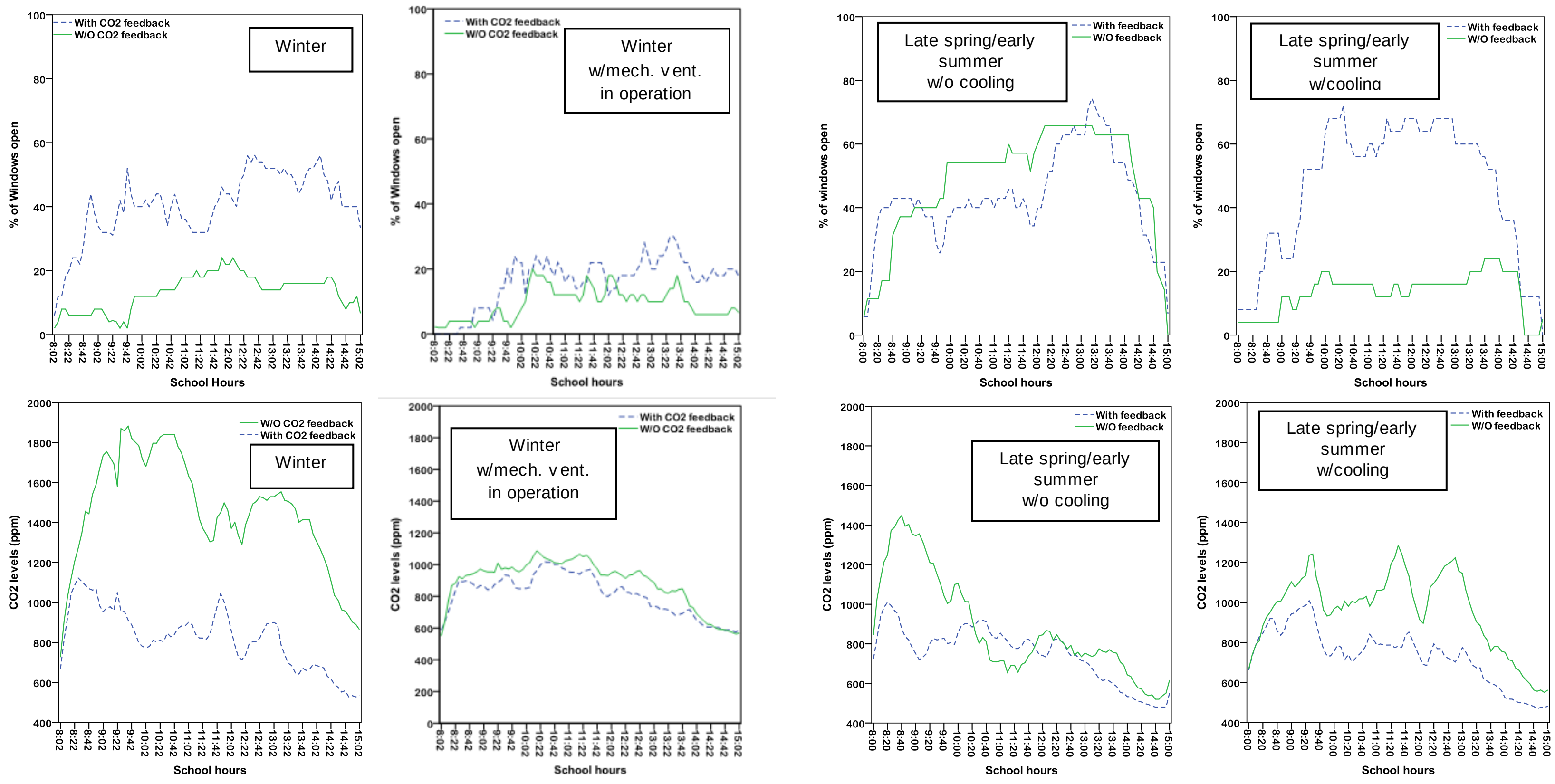

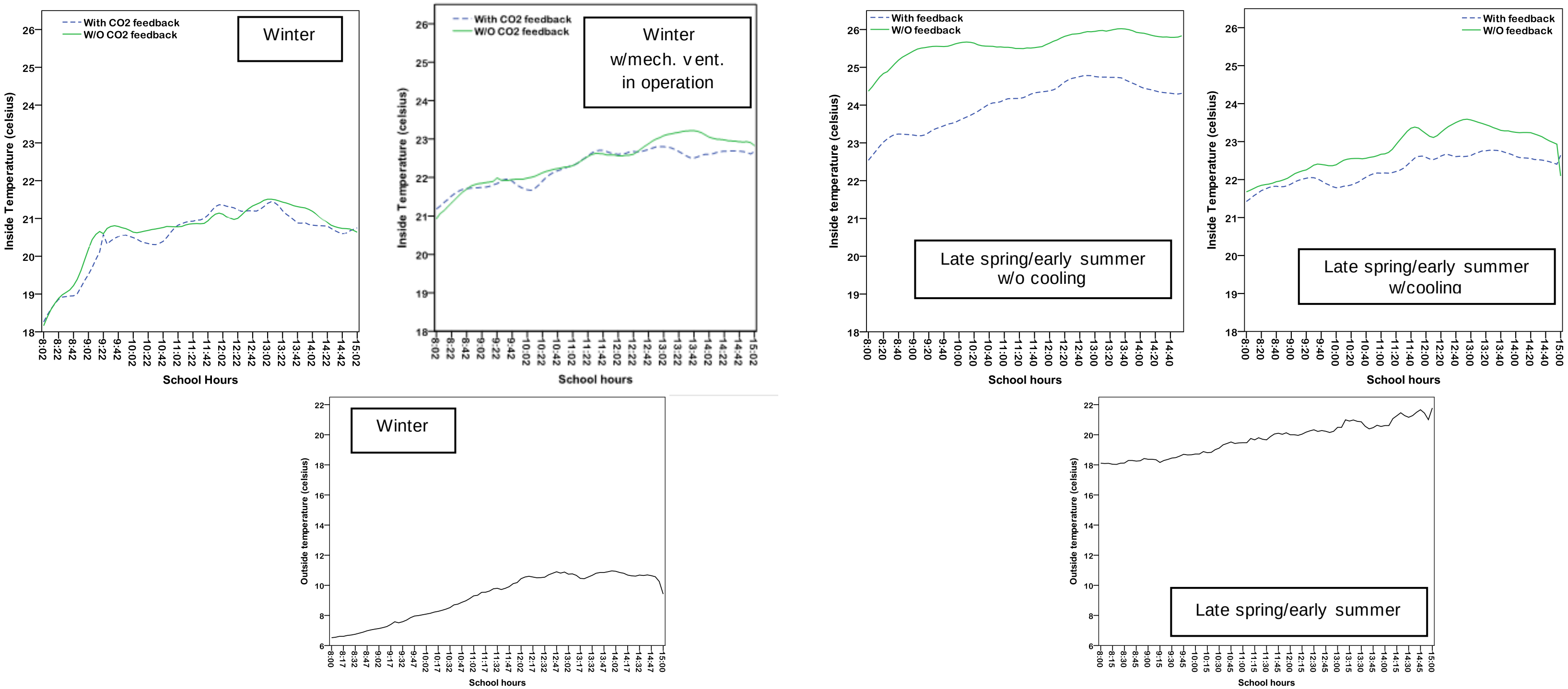

With CO2 feedback
W/O CO2 feedback
Winter
Inside Temperature (celsius)
School Hours
Winter w/mech. vent. in operation
School hours
With feedback
W/O feedback
Late spring/early summer w/o cooling
Inside temperature (celsius)
Late spring/early summer w/cooling
Outside temperature (celsius)
Late spring/early summer

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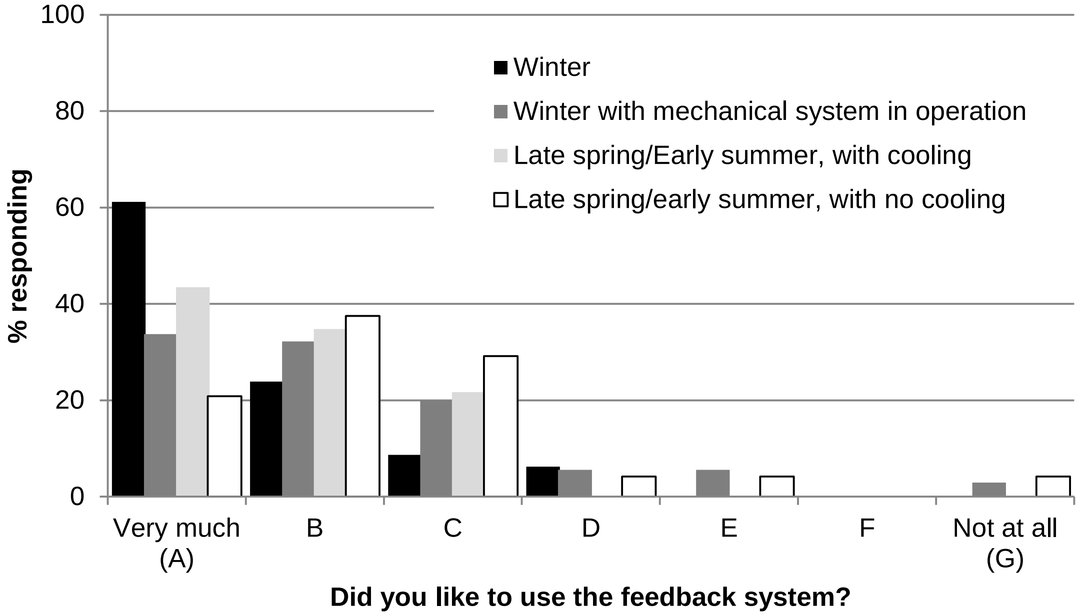

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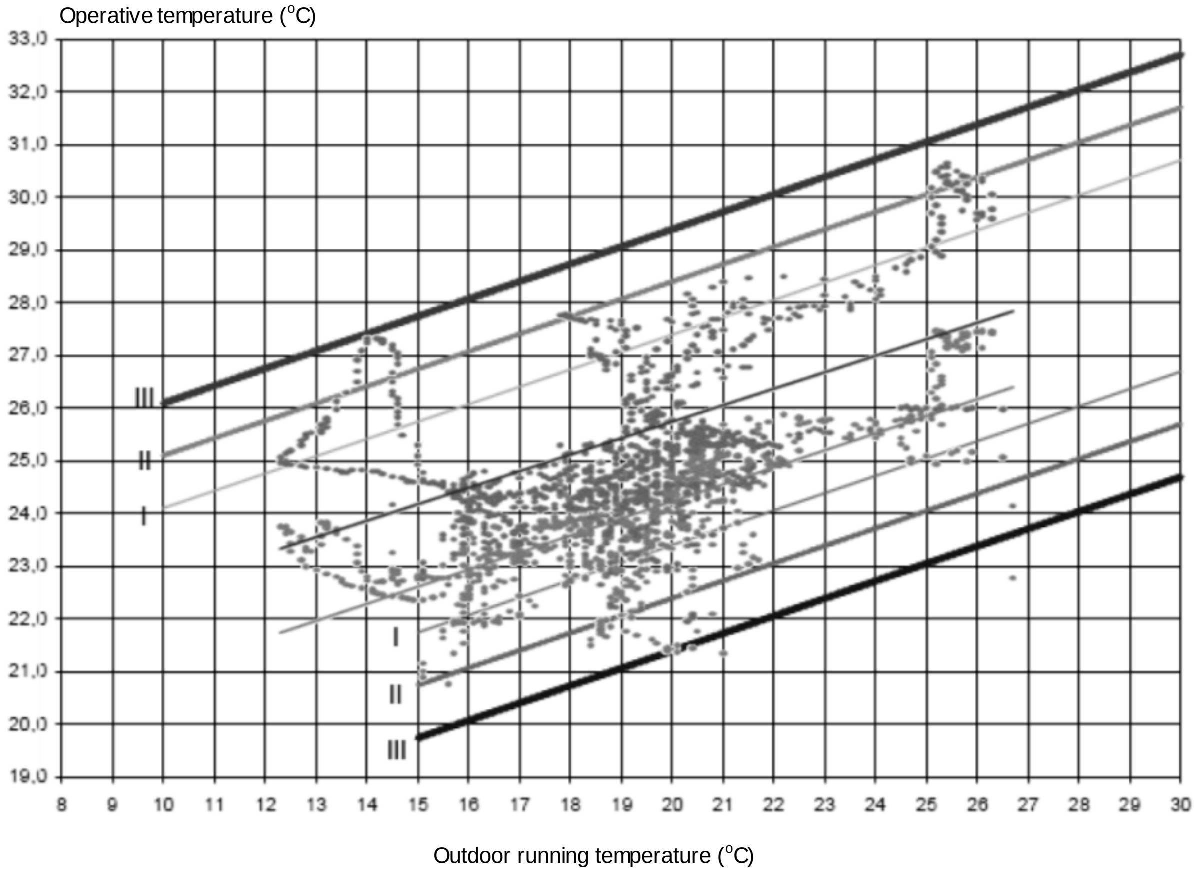

Table 1. Perceptions and symptoms indicated by pupils on the scale illustrated in Figure 1 Medians [25^{th} percentile -75^{th} percentile]; P-values show whether the differences between classrooms with and without visual CO_2 feedback were significant

	Heating Season (Winter) Classroom w/o mechanical ventilation			Heating Season (Winter) Classroom with mechanical ventilation			Cooling Season (Late Spring/Early Summer) Classroom w/o mechanical ventilation system and with no cooling			Cooling Season (Late Spring/Early Summer) Classroom w/o mechanical ventilation system and with cooling		
	With CO_2 feedback (n=43)	w/o CO_2 feedback (n=43)	P (Wilcoxon)	With CO_2 feedback (n=34)	w/o CO_2 feedback (n=34)	P (Wilcoxon)	With CO_2 feedback (n=47)	w/o CO_2 feedback (n=46)	P (Mann-Whitney)	With CO_2 feedback (n=23)	w/o CO_2 feedback (n=21)	P (Mann-Whithey)
How was the classroom environment during the week?												
Very Good (7)-Very Bad (1)	6 [5-6,5]	6 [5-6,5]	0,75	5[5-6]	5[4-5]	0,005*	5,5 [5-6]	5 [3-5]	0,001*	6 [5-6]	6 [6-7]	0,18
How was the classroom this week?												
Too cold (7)-Too warm (1)	4 [4-5]	4 [3-5]	0,35	4[3-5]	4[2-5]	0,22	4 [3-4]	2 [2-3]	<0.001*	4 [3-5]	5 [4-5]	0,15
Air was fresh (7)-Air was poor (1)	5 [4,5-6]	5 [4-6]	0,15	4[4-6]	4[2-5]	0,018*	5 [3-5]	3 [2-4]	0,001*	5 [5-6]	6 [5-6]	0,2
Air was still (7)–Air was drafty (1)	5 [4-6]	6 [4,5-6,5]	0,19	5[3-6]	4,5[3-7]	0,87	6 [5-7]	4 [3-5]	<0.001*	6 [5-7]	6 [5-7]	0,41
Too much noise (7)-Too silent (1)	5 [4-5]	5 [4-5]	0,27	4,5[4-5]	5[4-5]	0,41	4 [4-5]	4 [3-4]	0,03*	5 [5-6]	4 [4-4]	0,001
Too Humid (7)-Too dry (1)	4 [4-4]	4 [4-4]	0,84	4[3-4]	4[3-4]	0,81	4 [4-4]	4 [3-4]	0,02*	4 [4-5]	4 [4-4]	0,72
Too much light (7)-Too little light (1)	4 [4-4,5]	4 [3-5]	0,22	4[4-5]	4[4-5]	0,24	4 [4-5]	4 [3-4]	0,2	4 [4-4]	4 [4-5]	0,22
How did you felt this week, while you were in school?												
Could breathe freely (7)-Nose blocked (1)	6 [5-7]	6 [4-6,5]	0,32	5[4-6]	4[3-5]	0,015*	6 [4-6]	4 [3-5]	0,001*	6 [5-7]	6 [6-7]	0,21
Not tired (7)-felt very tired (1)	5 [4-6]	5 [3-6]	0,18	3,5[3-5]	3[2-4]	0,03*	4 [3-6]	3 [2-5]	0,2	5 [4-6]	5 [3-6]	0,8
No headache (7)-severe headache (1)	6 [5-7]	6 [3,5-7]	0,23	5[3-6]	4[3-5]	0,026*	5,5 [4-7]	4 [2-7]	0,06	6 [5-7]	6 [5-7]	0,6
Felt like working (7)-felt not like working (1)	6 [5-6]	5 [4-6]	0,02*	5[4-6]	4[3-5]	0,17	6 [5-6]	4,5 [4-5]	0,005*	6 [5-6]	6 [4-6]	0,88
Not dry lips (7)-dry lips (1)	6 [4-7]	5 [4-7]	0,12	5[4-6]	4[3-5]	0,014*	6 [4-7]	5 [3-7]	0,15	6 [5-7]	6 [2-6]	0,23
Not dry skin (7)-dry skin (1)	6 [4-7]	5 [4-7]	0,79	5[3-6]	4[3-6]	0,44	6 [5-7]	3 [6-7]	0,1	7 [6-7]	6 [4-7]	0,21
Not dry throat (7)-dry Throat (1)	6 [5-7]	6 [4-7]	0,05*	5[4-6]	4[3-6]	0,06*	6 [5-7]	5 [3-7]	0,11	6 [5-7]	6 [4-7]	0,71
Felt good (7)-not felt good (1)	7 [6-7]	6 [5-7]	0,02*	5[5-6]	5[4-6]	0,12	6 [5-7]	6 [3-7]	0,29	6 [6-7]	7 [5-7]	0,9

Table 2. Simulated (IDA-ICE 4) annual energy demand [kWh] for heating and cooling in classrooms with and without visual CO_2 feedback

	Classrooms w/o mechanical ventilation system				Classrooms with mechanical ventilation system	
	Heating demand		Cooling demand		Heating demand	
	With feedback	W/o feedback	With feedback	W/o feedback	With feedback	W/o feedback
August	4.7	4.2	34.1	41.9	4.8	4.4
September	85.3	67.4	21.5	28.6	70.3	46.1
October	335.2	277.5	0	0	300.4	227.9
November	1027	893.6	0	0	890.4	724.5
December	1513	1343	0	0	1320	1099
January	1473	1315	0	0	1291	1088
February	1242	1088	0	0	1065	869.3
March	845.7	716.5	0	0.1	708.4	553.4
April	368.2	299.1	9.3	13.1	292.5	206.2
May	36	29.4	39.5	50.9	29.4	20.8
June	0	0	65.4	72.6	0	0
TOTAL	6930	6034	170	207	5972	4840
% change (p.a.)	15%		-18%		23%	

Ventilation System Type, Classroom Environmental Quality and Pupils' Perceptions and Symptoms

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Abstract

The present study investigated indoor climate and window opening behaviour by pupils, as well as their perceptions and symptoms in classrooms with different types of ventilation systems. Four classrooms were selected in the same school in suburban Denmark. They were either aired by manually operable windows, or ventilated by automatically operable windows with and without an exhaust fan in operation, or by a balanced mechanical ventilation system. Indoor air temperature, relative humidity, carbon dioxide (CO2) concentration and window opening were continuously monitored for one month in non-heating and heating seasons; CO2 concentration was used to estimate average classroom ventilation rates. At the end of each measuring period, the pupils were asked to report their perceptions of the indoor environment and their acute health-related symptoms. The classroom aired by manually operable windows had the highest air temperatures and CO2 concentrations during both non-heating and heating season; the estimated average air-change rate was lowest in this classroom. The classroom with mechanical ventilation had the highest estimated average air-change rate. Windows were frequently opened in all four classrooms in the non-heating season but very seldom in the heating season. Automatic operation of the windows had a marked effect on CO2 concentration and classroom temperature in the heating season. Perceptions of the indoor environment were more positive in the classroom that was ventilated by automatically operable windows with an exhaust fan in operation: fewer symptoms were reported in this classroom compared with classrooms with other systems. Automatically operable windows with an exhaust fan and a mechanical ventilation system seem to be comparable alternatives for classroom ventilation though the energy consequences of each of these systems must be assessed before a final recommendation can be made.

Keywords: Ventilation system type, Temperature, Carbon dioxide, Window opening, Perception and Symptom

1. Introduction

The main purpose of classroom ventilation is to create indoor environmental conditions that reduce the risk of health problems among pupils and minimise their discomfort, to eliminate any negative effects on learning. Recent experiments show that inadequate ventilation rates in classrooms can result in a high prevalence of acute health symptoms, better known as Building Related symptoms or Sick Building Syndrome symptoms [1-4]. Inadequate classroom ventilation can also reduce the speed at which language-based and mathematical tasks that are typical of schoolwork are performed by pupils [5-6], and can reduce progress in learning as measured by the number of pupils who pass standard mathematics and language tests [7]. It can also increase absenteeism [8-9], which is likely to have negative consequences for learning. These effects can give rise to significant socio-economic costs [10-11]. In spite of this growing body of evidence, most of the data published in the scientific literature indicate that classroom ventilation in many schools is inadequate and that the outdoor air supply rates in schools are considerably lower than in offices, in many cases even lower than those observed in dwellings [1, 12-15].

Classroom ventilation is still provided in most schools by expecting teachers and pupils to open the windows. An increasing number of school classrooms are being fitted with automatically operable windows, extract ventilation using exhaust fans or mechanical ventilation systems with balanced supply and exhaust from a central or local air handling unit, but there are as yet no systematic data on the performance of these various types of ventilation in schools, especially as regards their impact on the indoor climate in classrooms, on the health of pupils and teachers or on learning. There is also very little data on the window opening behaviour of pupils and its effect on classroom ventilation.

Mumovic et al. carried out measurements in three new secondary schools during the heating season in the UK; the ventilation systems studied included automatically operable windows, exhaust (extract) ventilation and balanced mechanical ventilation [16-17]. They found that regardless of the type of ventilation system, most classrooms met the requirements of the Building Bulletin 101 regarding daily average CO2 concentration, which in the UK should not exceed 1,500 ppm [18].

Perna et al. studied several alternative ventilation strategies in a school in Italy to collect data on the optimization of indoor environmental quality and energy consumption [19]. The following three ventilation strategies were compared with a basic ventilation strategy: (1) natural ventilation, in which the windows were opened and closed by the users according to the indicated indoor CO2 concentration; (2) mechanical ventilation with constant airflow; (3) a wind driven exhaust fan (extractor) installed in the classroom ceiling. The classrooms with natural ventilation and a CO2 feedback display and with the wind driven exhaust fan (extractor) had acceptable environmental quality according to the Standard EN 15251[20], but the energy consumption of both of these systems was higher than that of mechanical ventilation.

Kinshella et al. examined indoor climate conditions in elementary schools with unit ventilators (fan coils), a constant air volume system and a variable air volume system [21]. The results showed that schools ventilated with constant air volume had the highest outdoor air supply rates and those with unit ventilators (fan coils) had the lowest. The prevalence of symptoms experienced by the faculty and staff was lowest in schools with variable air volume and the highest in the classrooms with unit ventilators; complaints of nasal congestion, sore throat, headache, and dustiness were among the more frequently reported symptoms.

Wålinder et al. investigated the influence of ventilation rates and ventilation system type on the nasal symptoms of school personnel in randomly selected primary schools in Sweden [22]. They found that nasal symptoms were worse in the mechanically ventilated classrooms (with balanced supply and exhaust) than in the naturally ventilated classrooms, even though the former had higher air exchange rates. The only exception was the mechanically ventilated classrooms with displacement ventilation, in which nasal symptoms were less frequent. Poor maintenance of the mechanical ventilation systems was presumed to be the reason for the observed results. This presumption is supported by Seppänen et al., who showed that the risk of Sick Building Syndrome symptoms in commercial buildings with mechanical ventilation systems is greater than in naturally ventilated buildings (presumably aired by manually operable windows) or in buildings with extract ventilation only [23-24].

Airing of classrooms by manual opening of windows depends to a high degree on outdoor conditions, including the location of the school (urban and/or rural) and climatic conditions (wind speed and direction, outdoor temperatures), as well as on window opening behaviour of pupils and teachers. Wargocki and Silva investigated to what extent the feedback system informing pupils when operable windows should be opened in classrooms can influence classroom temperature and air quality [25]. They showed that providing a visual indication that classroom ventilation is inadequate (classroom CO2 level was used for this purpose) caused pupils to open the windows more frequently. They also showed that providing mechanical cooling in the classrooms would restrict window opening, resulting in poor air quality, and concluded that classroom temperature rather than poor air quality is likely to be the main reason why windows are opened by pupils in schools.

Danish Building Regulations require that outdoor air supply rates must be no less than 5 L/s per person plus 0.35 L/s per m² floor area [26]. CO2 should not exceed 0.1% (1,000 ppm) according to the Danish Working Environment Authority. Recent measurements in schools in three Scandinavian countries showed that 56% of 743 classrooms in 320 schools in Denmark had CO2 concentrations higher than 1,000 ppm, especially in classrooms without balanced mechanical ventilation system, i.e. ventilated by opening the windows or only by exhaust fan [13]. In comparison, CO2 levels below 1,000 ppm were measured in 84% of 238 classrooms in 135 schools in Sweden and in 79% of 448 classrooms in 170 schools in Norway [13].These results suggested that the ventilation in many Danish classrooms/schools is inadequate and must be improved to ensure that the conditions do not have a negative effect on health and the performance of schoolwork. This can be achieved by upgrading existing ventilation systems. However, systematic data on the performance of different ventilation systems in schools is lacking, although a recent review of published data on ventilation in schools showed that the median CO2 level was 1,400 ppm in 900 naturally ventilated classrooms while it was only 910 ppm in 287 mechanically ventilated classrooms [12].

The main objective of the present work was to provide data on how different ventilation systems influence the conditions in classrooms, the window opening behaviour by children and teachers, pupil’s perceptions of the environment in classrooms and their health symptoms.

2. Methodology

2.1 The school and the classrooms

The study was performed in an elementary Danish school built of bricks and concrete in the early 1970s. The school is situated in a suburban area with low-rise buildings (Fig.1). The classrooms are located in three buildings, Wing A, Wing B and the main building (Fig.2). The ventilation in the classrooms in Wing A and Wing B is by automatically operated windows, each classroom being equipped with three automatically operated windows at the upper level. An exhaust fan is mounted in the ceiling of each classroom to provide additional ventilation when natural ventilation is inadequate. Each classroom has two windows in the lower part of a window section and one garden door. They can be opened manually by children and teachers if needed. The classrooms were retrofitted with automatically operable windows and exhaust fans during a major renovation of Wings A and B that was performed in the last decade. The classrooms in the main building are ventilated by a balanced mechanical ventilation system. They also have two windows and one garden door that can be opened manually by pupils and teachers. All windows and garden doors face the schoolyard or the green areas surrounding the school.

Fig.1 Plan view of the school

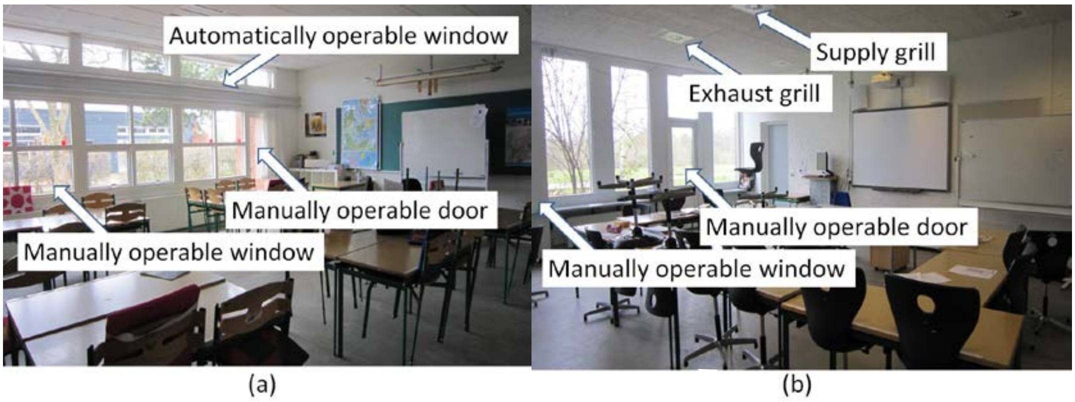


Fig.2 The classrooms in Wings A & B and the main building

The operation of the automatic windows and the exhaust fan is controlled with a specially developed system. The prime control is provided by sensors located centrally in the classroom, which measure classroom temperature and CO_2 concentration. The feedback from the sensors controls the degree of window opening and the fan speed. The fan speed is increased gradually as the CO_2 concentration in the classroom increases; the degree of window opening is similarly adjusted depending on the conditions in the classroom. The controller takes account of class schedules and the pre-determined window opening protocol. The signal from the sensors and the pre-determined control protocol is overruled if weather conditions preclude open windows, for example, when the wind is too strong. A mechanical ventilation system in the main building operates between 6:00 and 16:00 in the non-heating season and from 6:00 to 13:00 in the heating season; the filters are changed once a year in July. The school hours are generally from 8:00 to 14:00 on schooldays.

For the purpose of the present measurements, three classrooms were selected in Wing A and one classroom in the main building; their typology is presented in Table 1.The classrooms in Wing A were occupied by pupils from the 4th and the 5th grade while the classroom in the main building was occupied by pupils from the 8th and 9th grade. The control of the automatically operated windows and the fan speed in two classrooms in Wing A was modified to create two different modes of ventilation representative of single-sided ventilation with either manually or automatically operable windows; the control in the third classroom remained unchanged. In one classroom, the automatically operated windows and the exhaust fan were idled so that the classroom could only be aired by opening windows manually. In another classroom, the exhaust fan was idled but the automatic opening of windows remained unchanged. No changes were made to the ventilation system in the main building.

Table 1 Typology of classrooms in which the measurements were performed; all classrooms could be aired by windows/garden doors that could be opened manually by pupils and/or teachers (MW = classrooms with manually operable windows only, AW = classrooms with automatically operable windows w/o exhaust fan, AW/EF = classrooms with automatically operable windows with exhaust fan, MV = classrooms with mechanical ventilation system)

Class-room	Acronym	Description of ventilation systems	Average occupancy		Space volume (m^3)	Floor area (m^2)
			Non-heating season	Heating season		
1	MW	Classroom aired by manually operable windows	22	19	123.5	49.4
2	AW	Classroom aired primarily by automatically operable window	24	22	123.5	49.4
3	AW/EF	Classroom aired primarily by automatically operable window with exhaust fan	25	24	123.5	49.4
4	MV	Classroom aired primarily by the mechanical ventilation system	20	16	180	72

In addition to the above methods of ventilation, all classrooms participating in the experiments preserved the possibility for airing by manual opening of the windows or garden doors. The pupils and the teachers were not especially instructed as to how the classrooms should be aired with manually operable windows and garden doors and they could open and close them according to their established habits. Other classroom routines were not modified during the measurements. Neither teacher nor pupils were informed about the changes made to the system controlling the automatically operated windows and the operation of exhaust fans.

2.2 Indoor climate measurements

The measurements were performed in two periods, from May 9 to June 8, 2012 (in the non-heating season) and from November 20 to December 20, 2012 (in the heating season).

In each classroom the following measurements were carried out: CO_2 concentration measured using a VAISALA GM20D sensor (accuracy: ±30ppm + 2% of the reading) connected to a HOBO U12 logger which also recorded the classroom temperature and relative humidity (RH) (accuracy: ±0.7℃ and ±5% RH, respectively); opening of windows and garden doors was registered using HOBO State loggers; State loggers and magnetic blocks were attached to the frame of each window/door in every classroom participating in the measurements. Only the data from the periods when pupils were present in the classrooms were used in the subsequent analyses. Outdoor temperature and RH were measured in parallel with the indoor measurements by the weather station used to control the automatic opening of windows. Outdoor levels of ozone and PM2.5 and PM10 were not measured; instead, they were obtained from an outdoor monitoring station located in the suburban area at a distance of about 25-30 km from the school where the measurements took place.

Classroom ventilation rate was estimated using the average of the peak values of CO_2 concentration measured during school hours; it was assumed that the peak CO_2 is indicative of steady-state CO_2 concentration levels and could be used to estimate the minimum ventilation rate [27]. The CO_2 generation rate per pupil was assumed to be 0.004 L/s and per teacher to be 0.0054 L/s [28]. The outdoor CO_2 was not monitored. It was assumed 350 ppm; this was the concentration measured on average in classrooms at night. The rate at which the classroom was ventilated by the mechanical ventilation system was additionally measured using a Flow Finder 153 by the hood method with zero pressure compensation (accuracy: 5% of reading with a minimum value of 2 m^3/h); the air flow delivered by the supply terminals and extracted by the exhaust grills was measured during normal operation of the system. The air tightness of the classrooms was not measured.

2.3 Perceptions and health symptoms

In the last week of each measuring period, on Thursday or Friday before the lunch break, the pupils were asked to complete questionnaires on their perception of the classroom environment and the intensity of any acute health-related symptoms; the recall time was the week preceding the distribution of these questionnaires. The following perceptions were collected: quality of classroom environment, thermal environment, classroom air quality, air movement, acoustic environment in the classroom, air humidity and illumination. The following symptoms were assessed: ability to breathe, fatigue, headache, willingness to learn, dryness of lips, skin and throat, and general mood. The detailed questions used in the questionnaire are shown in Table 4 and 5.

The scales used to collect the perceptions and symptoms were modified visual-analogue scales in which the continuous line was replaced by a set of seven “smileys” (Fig. 3). It was hoped that this type of scale would be more intuitive and more easily understood by the pupils. Ninety-one questionnaires were distributed during the non-heating season and 86 were returned (response rate of 95%). Eighty-one questionnaires were distributed at the end of measurement during the heating season and 77 were returned (response rate of 95%).

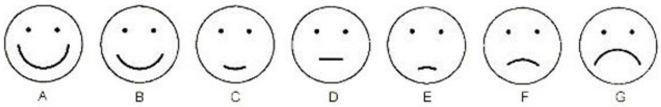


Fig.3 An example of a scale used to obtain the perceptions and symptoms of pupils. For analysis, the scale was coded as follows: A=1, B=2, C=3, D=4, E=5, F=6 and G=7.

2.4 Statistical analysis

The Kruskal-Wallis test was used to compare perceptions and symptoms in classrooms ventilated using different methods; a post-hoc analysis was performed only when the differences were statistically significant, as recommended by Siegel and Castellan [29].The Spearman rank-order correlation coefficient was calculated to examine the correlation between the perceptions and symptoms reported by the pupils and the measured indoor environmental parameters. The Mann-Whitney U-test was used to examine the differences between perceptions and symptoms in the non-heating and heating seasons. Independent two-sample t-tests were used to compare temperatures, relative humidities and CO_2 concentrations measured in the classrooms in the non-heating and heating seasons. The significance level was set at P=0.05, 2-tail.

3. Results

3.1 Ambient air

During the measurements in the non-heating season, the outdoor temperatures were between 2.5℃ and 30.5℃ with an average of 15.9±5.9℃. The average 24-hour particle concentration in the ambient air ranged from 7.5 to 28.4 µg/m^3 for PM10 and 3.1 to 25.6 µg/m3 for PM2.5; the hourly ozone concentration ranged between 7.7 and 73.8 ppb. During the measurements in the heating season the outdoor temperatures were between -7.3℃ and 10.9℃ with an average of 1.9±4.2℃. The average 24-hour particle concentration in the ambient air ranged from 1.8 to 51.9 µg/m^3 for PM10 and from 2.1 to 33.1 µg/m3 for PM2.5; the hourly ozone concentration during this period was between 0 and 39 ppb. The 2012 annual outdoor particle concentration was 15.8 µg/m^3 for PM10 and 9.6 µg/m^3 for PM2.5. The annual mean concentration of ozone was 30.8 ppb. PM concentrations were generally higher (average and peak levels) in winter months (heating season) and ozone concentration was higher during summer months (non-heating season).

3.2 Indoor climate, ventilation and window opening behavior

Measured classroom temperatures in the non-heating season were significantly higher than those in the heating season (Table 2). Average classroom temperatures measured in different classrooms were not alike. The highest temperature (about 25℃) was measured in the classroom, which could only be aired by opening the manually operable windows/garden door, and the lowest temperature was measured in the mechanically ventilated classroom. In the former classroom, the temperature was stable throughout the school day, while in the latter it increased during each school day by about 2℃; temperatures also increased in the classrooms with automatically operable windows, but the rate of change was slightly lower than in the mechanically ventilated classroom, about 1.5℃ (Figure 4). In the heating season, the average temperature in all classrooms was fairly similar, about 22℃ (Table 2). Again, the temperature in the mechanically ventilated classroom increased in the course of each school day, this time on average by nearly 3.5℃, but was on average only about 19℃ at the start of the school day. The temperatures were otherwise fairly stable in all other classrooms where the measurements were performed; the fluctuations were below 1℃ (Figure 5).

Table 2 Measured classroom temperatures, relative humidities and CO_2 concentrations during the school hours (Mean±SD) (MW = classrooms with manually operable windows only, AW = classrooms with automatically operable windows w/o exhaust fan, AW/EF = classrooms with automatically operable windows with exhaust fan, MV = classrooms with mechanical ventilation system)

	Non-heating season				Heating season			
	MW	AW	AW/EF	MV	MW	AW	AW/EF	MV
Temperature (℃)	25.4±0.2	24.6±0.6	24.4±0.3	23.7± 0.6	22.0±0.4	21.8±0.3	22.2±0.3	21.1±1.0
Relative humidity (%)	43.9±0.5	43.7±0.9	42.1±0.5	41.3±0.8	44.5±1.7	38.5±0.92	42.3±0.8	37.1±0.8
CO_2 (ppm)	803 ±184	732±131	662 ±96	619±95	1458±436	1079±248	942±185	757±147

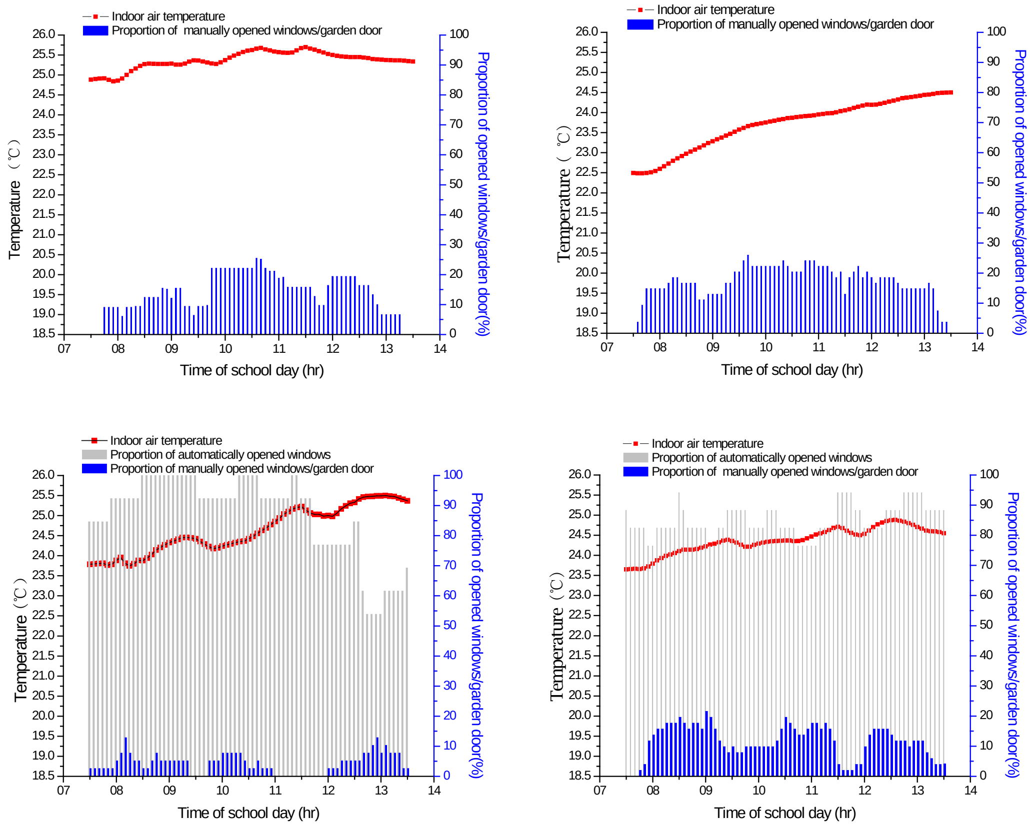
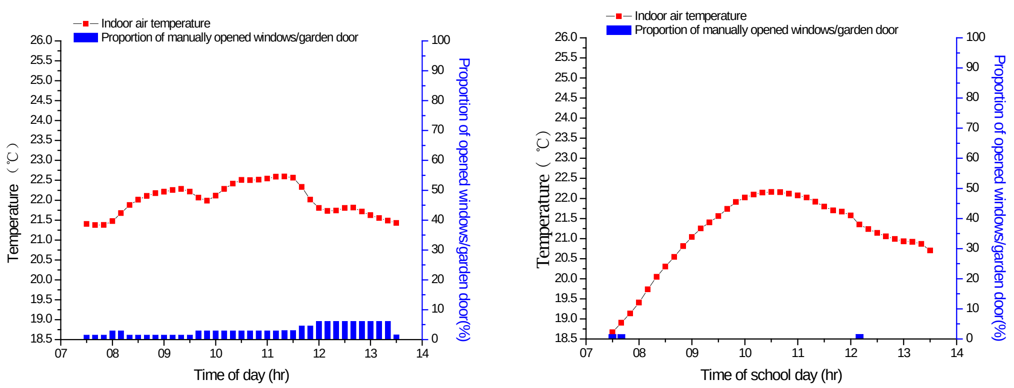


Fig.4 Time weighted average temperature and window/garden door opening in the non-heating season (May) in the classrooms with manually operable windows only - MW (left upper corner), with mechanical ventilation system - MV (right upper corner), with automatically operable windows w/o exhaust fan- AW (left lower corner) and with automatically operable windows with exhaust fan - AW/EF (right lower corner)



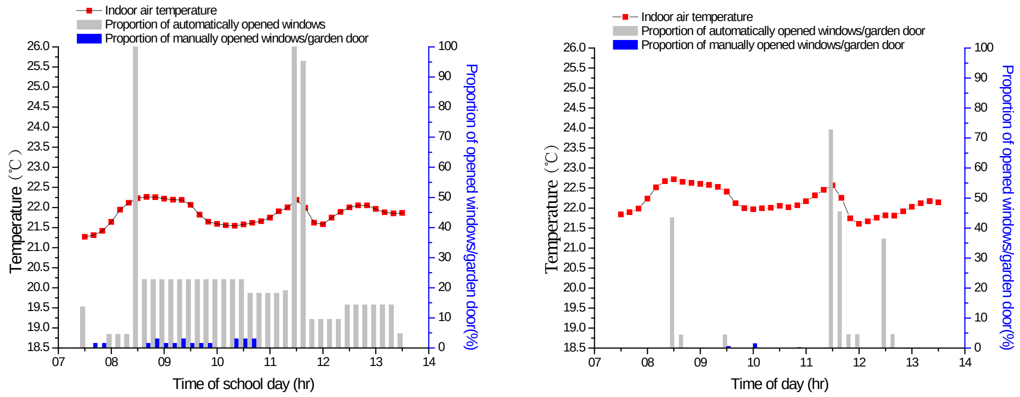
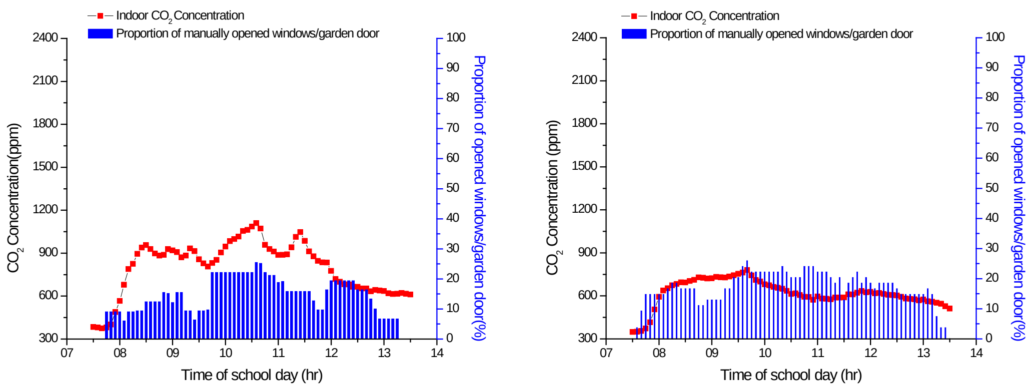


Fig.5 Time weighted average temperature and window/garden door opening in the heating season (November-December) in the classrooms with manually operable windows only - MW (left upper corner), with mechanical ventilation system - MV (right upper corner), with automatically operable windows w/o exhaust fan- AW (left lower corner) and with automatically operable windows with exhaust fan - AW/EF (right lower corner)

The average relative humidity in the classrooms was about 35% to 45%. It was fairly similar independently of the season and the type of ventilation in the classroom (Table 2).

Measured average CO_2 concentrations in the classrooms were significantly lower in the non-heating season than in the heating season (Table 2). Average CO_2 concentration was below 1,000 ppm in the non-heating season in all classrooms and only in the classroom where windows had to be opened manually for airing was the peak concentration higher than 1,000 ppm, and then only for a short period in the middle of the day (Figure 6). There were clear differences in the average CO_2 concentration in classrooms during the heating season (Table 2). The highest concentration was measured in the classroom that was aired only by manually operable windows and the second highest in the classroom with automatically operable windows but no exhaust fan. The peak CO_2 concentration reached about 2,200 ppm in the former classroom and about 1,400 ppm in the latter (Figure 7). The average concentrations in the other two classrooms were below 1,000 ppm, with peak concentration being around 1,000-1,200 ppm (Figure 7). Figure 7 shows that when the CO_2 concentration reached a level close to the steady state, it stayed fairly stable in the remaining part of the day in all classrooms except for the classroom aired only by manually operable windows. The fluctuations in CO_2 concentration shown in Figures 6 and 7 reflect the routines in elementary schools in Denmark, with major breaks in the early morning (around 9.30-10.00) and in the late morning (around 11:30-12:00) [22].



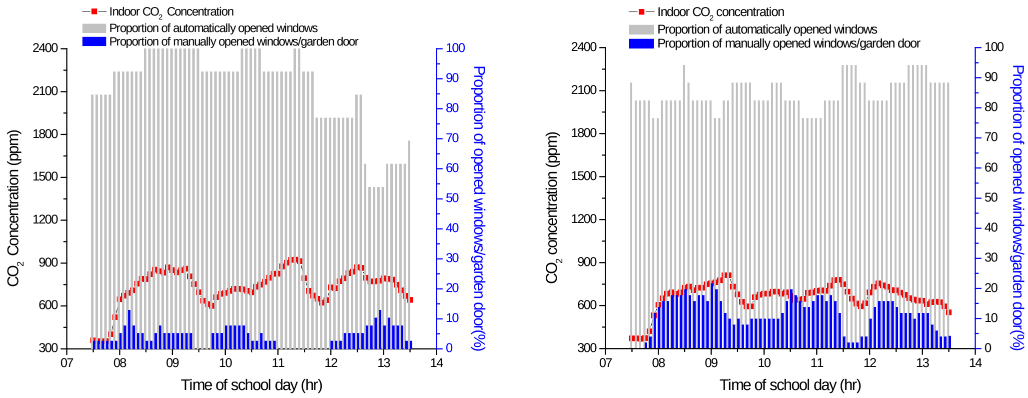


Fig.6 Time weighted average CO_2 concentration and window/garden door opening in the non-heating season (May) in the classrooms with manually operable windows only - MW (left upper corner), with mechanical ventilation system - MV (right upper corner), with automatically operable windows w/o exhaust fan- AW (left lower corner) and with automatically operable windows with exhaust fan - AW/EF (right lower corner)

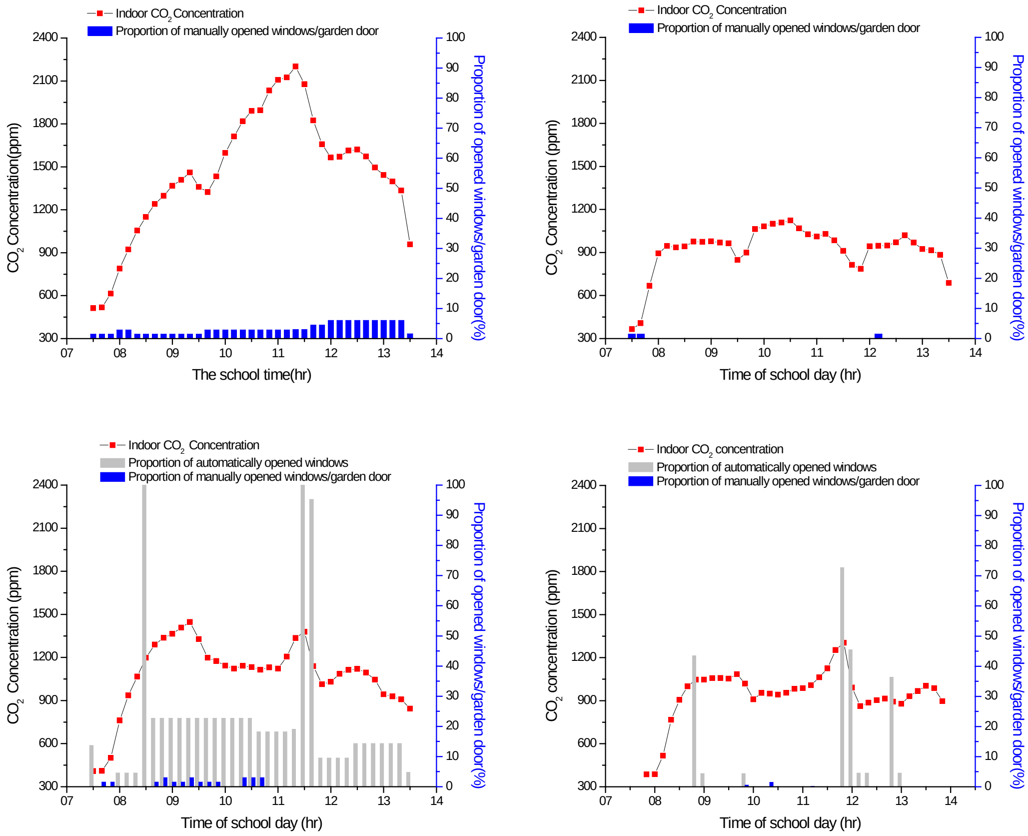


Fig.7 Time weighted average CO_2 concentration and window/garden door opening in the heating season (November-December) in the classrooms with manually operable windows only - MW (left upper corner), with mechanical ventilation system - MV (right upper corner), with automatically operable windows w/o exhaust fan- AW (left lower corner) and with automatically operable windows with exhaust fan - AW/EF (right lower corner)

Figures 4 to 7 show the time-weighted average indoor CO_2 concentration and temperature, and the proportion of opened windows/garden door in classrooms with different ventilation systems. The proportion represented the amount of opened windows/garden door divided by total amount of windows/garden door. Figs.4 to 7 showed that the windows/garden doors were opened more often in the non-heating season than in the heating season; this applies both to the automatically and manually operable windows. The percentage of manually operable windows/garden doors was lower in the classrooms with automatically operable windows in the non-heating season, while it was fairly similar in the classrooms which were aired by the manual opening of windows or by the mechanical ventilation system (Figs. 4 and 6). In the non-heating season, the windows were only opened in the classroom where airing could only be obtained by manually operating windows (Figs. 5 and 7).

Based on the number of opened windows and the duration of the opening registered by the loggers, the average time during which windows were open per day in different classrooms during the non-heating and heating season was calculated. The results presented in Table 3 show that manually operable windows/garden doors were opened less often in the heating season, and generally much longer in the classroom where the windows/garden door were opened manually as the only means to air the classroom. The total period during which all windows/garden doors (manually and automatically operable) were opened in different classrooms was much longer in the classrooms with automatically operable windows. This was the case especially in the non-heating season, when they were opened for almost the entire school day (on average 6 to 7 hours per day).

Figure 8 shows the average ventilation rates in the classrooms, estimated using the measured peak CO_2 concentrations during school hours. The estimated rates are expected to be mostly outdoor air supply rates as the internal doors to the classrooms were generally closed when lessons/teaching took place. Ventilation rates were lowest in the classroom aired by manually operable windows (ca. 2 to 4 L/s per person) and the highest in the classroom with the mechanical ventilation system (ca. 7.5 L/s per person). They were lower in the heating season, even in the classroom with a mechanical ventilation system. The higher rate in the classroom with mechanical ventilation system in the non-heating season can be attributed to extra air provided through manually opened windows/garden door. In the classroom with a mechanical ventilation system, the outdoor air supply rate measured at the supply and exhaust terminals using the hood method was about 7.5 L/s per person. This was close to the rate estimated using peak CO_2 concentration in the non-heating and heating season. The estimated ventilation rates correlate quite well with the average length of opening of windows/garden doors presented in Table 3: the longer the windows/garden doors were opened the higher were the estimated ventilation rates in the classrooms not ventilated by a mechanical system.

Table 3 Average length of window opening (hours per day) in classrooms with different ventilation systems (MW = classrooms with manually operable windows only, AW = classrooms with automatically operable windows w/o exhaust fan, AW/EF = classrooms with automatically operable windows with exhaust fan, MV = classrooms with mechanical ventilation system)

	Non-heating season				Heating season			
	MW	AW	AW/EF	MV	MW	AW	AW/EF	MV
Manually operable windows	0.7	0.1	0.6	0.0	0.4	0.0	0.0	0.0
Manually operable garden door	1.2	0.5	0.9	3.1	0.0	0.1	0.1	0.0
Automatically operable windows	N/A	5.3	5.2	N/A	N/A	1.3	0.5	N/A
Total	1.9	5.9	6.7	3.1	0.4	1.4	0.6	0.0

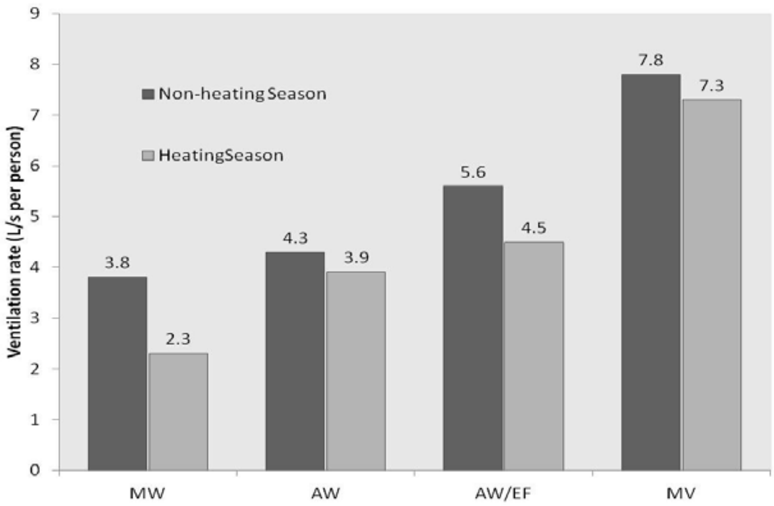


Fig.8 Ventilation rate estimated in the classrooms with different ventilation systems using peak concentrations of CO_2

3.2 Perceptions and symptoms

Assessments of classroom environment and the reported intensity of the acute health symptoms at the end of every measuring period are shown in Tables 4 and 5, respectively.

Table 4 shows that the classrooms with either a mechanical ventilation system or automatically operable windows with an exhaust fan were perceived to be significantly noisier than the other classrooms, both in the non-heating and heating season. The environment in the classroom with automatically operable windows with an exhaust fan was perceived to be significantly better than in the mechanically ventilated classroom, in both the non-heating and heating season. The classroom where windows/garden door had to be opened manually for airing was judged significantly warmer in the non-heating season compared to the classroom with automatically operable windows with an exhaust fan, which tallies with the measurements of temperature shown in Tab.2 and Fig.4. Classroom air was perceived to be significantly fresher in the non-heating season in the classroom with automatically operated windows with an exhaust fan compared to the classroom with only manually operable windows/garden door and to the mechanically ventilated classroom. No any other differences in the perceptions between classrooms with different ventilation principle reached formal statistical significance. Comparing the perceptions only in the classrooms without mechanical system did not affect most of the significant differences, which remained unchanged except for the assessments of the classroom environment in the non-heating season, which were not significantly different in classrooms without mechanical ventilation system. When the perceptions were compared between the non-heating and heating season, classrooms with manually operable windows/garden door, with automatically operable windows without exhaust fan and with mechanical ventilation were considered significantly warmer in the non-heating season compared to the heating season. The air was judged significantly less fresh in the heating season compared with the non-heating season in the classroom with automatically operable windows with an exhaust fan, while the air was judged to be significantly less still in this season in the mechanically ventilated classroom.

Table 5 shows that there were significant differences between the intensity of symptoms in the classrooms with different types of ventilation in the non-heating and heating season. In most of the cases, the intensity of symptoms was significantly higher in the classroom that was mechanically ventilated, while it was lower in the classroom with automatically operable windows with an exhaust fan. In the non-heating season, the intensity of many symptoms was also significantly higher in the classroom aired only by manual opening of windows and garden door compared to the classroom with automatically operable window and an exhaust fan. However, the same tendency was not seen in the heating season when CO_2 levels were higher and the estimated ventilation rates were lower. The likely reason are high temperatures in the non-heating season in classrooms with manually operable windows, previous experiments showing that elevated temperatures cause that air quality is perceived to be poor [30] and the acute health symptoms are exacerbated [31]. When the analyses were repeated excluding symptoms in the mechanically ventilated classroom, no significant differences were observed for the intensity of headache, dryness of lips and wellbeing (feeling good) in the non-heating season, while in the heating season significant differences were only found for skin dryness and wellbeing. In most cases, there were no significant differences in the intensity of symptoms between the non-heating and heating season in a given classroom. Only in the classroom with automatically operable windows and exhaust fan was the nose reported to be significantly more blocked and skin significantly drier in the heating season.

Table 6 shows that only in a few cases was there any significant correlation between the measured indoor climate parameters in the classrooms without mechanical ventilation system and the perceptions and symptoms reported by pupils. There was a positive and significant correlation between perceptions of feeling warm/cold and the measured air temperature. The perceptions of air quality and wellbeing were significantly correlated with the measured CO_2 concentration and the estimated ventilation rate. The reported intensity of blocked nose was significantly correlated with the relative humidity, while skin dryness correlated significantly with the estimated ventilation rate.

Table 4 Perceptions (mean±sd) in the classrooms with different ventilation systems; bold numbers indicate the perceptions between which the difference reached formal statistical significance (P<0.05) (MW = classrooms with manually operable windows only, AW = classrooms with automatically operable windows w/o exhaust fan, AW/EF = classrooms with automatically operable windows with exhaust fan, MV = classrooms with mechanical ventilation system)

	Non-heating season				Heating season			
	MW	AW	AW/EF	MV	MW	AW	AW/EF	MV
How was the classroom environment this week?(coding of the scale is shown in the brackets)								
Very good(1)-Very bad(7)	3.0±1.4	3.0±1.3	**2.3±1.2**	**3.4±1.1**	2,7±1,4	3,3±1,4	**2,3±1,1**	**3,9±1,6**
How was the classroom this week?(coding of the scale is shown in the brackets)								
Too cold(1)-Too warm(7)	**4.9±0,9**	4.0±0,9	**3.9±1,1**	4.5±1,3	3,8±1,3	3,9±1,4	3,9±0,5	3,4±1,4
Air was fresh(1)- Air was poor(7)	**4.0±1.6**	3.6±1.5	**2.8±1.7**	**4.5±1.2**	4,3±2,1	4,0±1,6	3,3±1,6	4,1±1,4
Air was still(1)- Air was draft (7)	2.4±1.3	3.4±1.1	2.1±1.5	2.5±1.7	3,2±2,1	3,3±1,5	2,3±1,2	3,7±1,5
Too silent (1)-Too noisy(7)	**2,5±0.7**	**2,7±1.1**	**3,6±0.8**	**3,6±1.0**	**2,6±1,1**	**2,7±1,1**	**3,7±0,9**	**4,1±1,2**
Too humid(1)-Too dry(7)	4,2±1,2	4,4±1,1	4,0±0,7	4,1±1,2	4,7±1,5	4,2±1,2	4,2±0,9	4,4±0,6
Too much light (1)-Too little light (7)	4,1±0,8	3,7±0,8	3,1±1,1	4,2±1,5	3,7±0,7	3,8±0,8	4,0±1,0	3,9±0,8

Table 5 Symptoms in classrooms with different ventilation systems; mean ±sd are shown. Bold numbers indicate the symptoms between which the difference reached formal statistical significance (P<0.05) (MW = classrooms with manually operable windows only, AW = classrooms with automatically operable windows w/o exhaust fan, AW/EF = classrooms with automatically operable windows with exhaust fan, MV = classrooms with mechanical ventilation system)

	Non-heating season	Heating season

	MW	AW	AW/EF	MV	MW	AW	AW/EF	MV
How did you feel this week while you were in school? (coding of the scale is shown in the brackets)								
Could breathe freely(1)-Nose blocked(7)	**3.6±2.1**	3.3±2.1	**1.8±1.0**	**3.4±1.9**	3,3±2,1	3,0±2,0	**2,7±1,6**	**3,9±1,5**
Not tired(1)-Felt very tired(7)	**4.4±1.6**	3.5±1.9	**2.9±1.7**	**5.1±1.4**	3,9±2,0	3,5±2,1	**3,2±1,7**	**4,3±1,4**
No headache(1)-Severe headache(7)	**2.1±1.4**	3.0±2.2	**2.4±1.8**	**4.1±1.9**	**2,4±1,6**	3,2±2,3	**2,7±1,8**	**4,2±1,6**
Felt like working (1)-Felt not like working(7)	**3.4±1.7**	2.9±1.5	**2.3±1.4**	**3.9±1.4**	**3,6±2,0**	3,3±1,9	**2,7±1,3**	**3,8±0,9**
Not dry lips(1)-Lips dry (7)	**2.6±1.2**	3.3±2.0	**2.6±1.8**	**4.3±1.9**	4,3±2,5	3,1±1,9	3,3±2,2	3,7±1,5
Not dry skin(1)-Skin dry (7)	**3.6±2.1**	2.7±1.8	**2.0±1.3**	**4.0±1.9**	**4,7±2,6**	3,1±2,0	**2,8±1,8**	**4,2±1,4**
Not dry throat(1)-Throat dry(7)	**3.6±1.9**	3.3±2.2	**2.1±1.1**	**3.6±1.8**	3,4±2,1	3,3±2,0	**2,7±1,5**	**4,1±1,4**
Felt good(1)-Felt not good(7)	2.5±1.6	3.0±2.2	**1.8±1.0**	**2.9±1.5**	2,8±1,8	3,1±1,9	**1,8±0,9**	**3,3±1,2**

Table 6 Correlation between indoor environmental parameters and perceptions and symptoms in all three naturally ventilated classrooms; the table shows the correlation coefficients; bold numbers are statistically significant ($P<0.05$)

	Air temperature(℃)	Relative humidity (%)	CO_2(ppm)	Ventilation rate (L/sp)
Very good(1)-Very bad(7)	-.086	-.143	.143	-.543
Too cold(1)-Too warm(7)	**1.000**	.371	-.714	.429
Air was fresh(1)- Air was poor(7)	-.429	.429	**.829**	**-1.000**
Air was still(1)- Air was draft (7)	-.143	.143	.314	-.600
Too silent (1)-Too noisy (7)	-.371	-.714	-.200	.657
Could breathe freely(1)-Nose blocked(7)	.087	**.841**	.464	-.696
Not tired(1)-Felt very tired(7)	.257	.086	.200	-.143
No headache(1)-Severe headache(7)	.486	.657	.143	-.543
Felt like working (1)-Felt not like working(7)	.314	.771	.371	-.714
Not dry lips(1)-Lips dry (7)	-.600	-.486	.314	-.200
Not dry skin(1)-Skin dry (7)	-.143	.657	.744	**-.943**
Not dry throat(1)-Throat dry(7)	-.314	.543	.600	-.543
Felt good(1)-Felt not good(7)	-.257	.600	**.829**	**-.886**

4. Discussion

During the non-heating season, the mean weighted classroom temperatures were generally between 22°C and 26°C (Figure 4). None of the classrooms had mechanical cooling installed so the observed thermal conditions in the classrooms should be evaluated by comparing them with the requirements of the adaptive model. For an average outdoor temperature of 15.9°C in the period when the measurements were taken in the non-heating season, the range of indoor operative temperatures following the adaptive thermal comfort model should be between 22°C and 26°C in spaces with a high level of expectation (≤10% persons dissatisfied with thermal environment), and between 20°C and 28°C in spaces with a moderate level of expectation (≤ 35% persons dissatisfied with thermal environment) [20]. The present measurements show that according to the requirements of standard EN 15251 [20] the classrooms can be generally classified as spaces where high expectations of thermal conditions are met independently of the type of ventilation system installed. The pupils still indicated that it was too warm in the classroom where the windows were opened manually to achieve proper airing of the classroom compared with the classrooms with other types of ventilation (Table 4). The thermal conditions in this classroom cannot thus be considered to fulfil the expectations of pupils, although the requirements of EN15251 for buildings without mechanical cooling were met.

During the heating season, the operative temperature should be within the range 19°C to 25°C, depending on the category of indoor space, with an average of 22°C [20]. The measured time-weighted air temperatures in all classrooms were generally within these limits, but in the morning hours, the temperatures were slightly below this range in the mechanically ventilated classroom (Figure 5). Following the requirements of standard EN15251 [20], the classrooms which did not have a mechanical ventilation system could thus be classified as spaces fulfilling a high level of expectation (≤6% persons dissatisfied with thermal environment), while the classroom with the mechanical ventilation system was a space that fulfilled only a moderate level of expectation (≤15% persons dissatisfied with thermal environment) because of the slightly lower temperatures in the morning. No complaints about the thermal environment were reported (Table 4), this time agreeing well with EN15251. The classrooms were heated by water-filled radiators placed under the windows. The radiators were equipped with thermostatic valves but their set points were not recorded during the measurements. The difference in temperatures in the classrooms could therefore have occurred due to different set points of these valves, which could be operated by the teachers and pupils according to their needs. This could be the reason why the temperatures were lower in the classroom with a mechanical ventilation system.

Danish Building Regulations stipulate that the ventilation rates in classrooms should be 5 L/s per person plus 0.35 L/s per m^2 of floor area, which corresponds to about 6 L/s per person [26]; it is also recommended by the Danish Working Environment Authority that CO_2 concentration should not be higher than 1,000 ppm. This recommendation was generally met in all classrooms in the non-heating season, although in the classroom where the windows had to be opened manually for airing there were short periods when the CO_2 concentration was above 1,000 ppm (Figure 6). The outdoor air supply rates estimated using peak CO_2 concentration (i.e. close to the minimum rates observed) met the requirements of the Danish Building Regulation only in the classroom with a mechanical ventilation system and were close to these requirements in the classroom with automatically operated windows with an exhaust fan (Figure 8). Surprisingly, the air quality was judged by pupils to be the worst in the mechanically ventilated classroom (Table 4). The reason for this is unknown but may be due to airborne pollutants from the ventilation system itself, especially from the ventilation filters installed in the system, which had been in use for about one year prior to the period when the measurements were carried out during the non-heating season (filters are changed once a year in July). Used filters have been shown in the past to be one of the main sources of pollution in the ventilation system [23-24, 32-34]. It may also be the case that emissions from building materials, furniture and decoration materials contributed to the observed results. The classroom with mechanical ventilation was located in an old building, while all the other classrooms were located in the same building (Wing A) which had been recently renovated. This may have been achieved using materials with low emissions, as it certainly should have been, but no chemical measurements were made to confirm this speculation.

During the heating season, CO_2 concentrations were close to or higher than 1,000 ppm in all classrooms (Figure 7); the highest concentration was measured in the classroom where windows had to be opened manually to achieve proper airing. The estimated ventilation rates were lower than in the non-heating season and only the classroom with the mechanical system fulfilled the requirements of the Danish Building Regulation (Table 4). The lower ventilation rates are most likely the consequence of the less frequently opened windows, both manually and automatically

(Figs. 6 and 7). Lower outdoor temperature cause cold drafts indoors, which may have caused that the windows were opened less often by pupils. Unfavourable weather conditions outdoors with strong winds (which are typical in Denmark in this season) may have caused the control of the automatically operable windows to be over-ridden so that windows remained closed although they would otherwise have been opened. This illustrates one of the limitations of this ventilation solution and the need for installing an alternate system that can provide the ventilation when windows have to remain closed due to unfavourable weather conditions.

The windows were opened nearly all the time during the non-heating season; this was so even in the classroom with a mechanical ventilation system, which suggests that window opening is to a large extent affected by the habits and customs of the occupants, especially considering that one of the main driving factors for window opening is the indoor temperature [35], which was relatively low in this classroom. As mentioned earlier, the windows were opened less frequently in the heating season. The period during which manually opened windows in the non-heating season were open was longer in the classroom where the automatically operable windows and the exhaust fan had been idled. This attempt by occupants to reduce the temperatures and the CO_2 concentrations in this classroom did however fail, as the measured values were still higher than in any of the other three classrooms. Figures 4 and 6 do not indicate a clear relationship between opened windows and classroom temperature and CO_2 concentration. Figure 7, which shows the measurements made during the heating season, indicates a much clearer relationship between CO_2 levels and window opening behaviour, especially in the classrooms with automatically operable windows. The window opening behaviour in both the non-heating and heating seasons are in agreement with the study of Wargocki and da Silva [25]. The limitation of the present study and the study of Wargocki and da Silva was that the classrooms were not especially designed for one-sided natural ventilation, as no special openings and/or slots had been provided on the wall opposite to the windows, to promote cross-ventilation, which could therefore only occur when the internal classroom doors were opened. Measurements in classrooms with properly designed one-sided natural ventilation are thus necessary to supplement the present results. Furthermore, in the present study the teachers and pupils were accustomed to having automatically operable windows even in the classroom where they were idled. This could to some extent influence and reduce the number of windows that were opened manually, especially at the beginning of a 1-month measuring period. Because the outdoor temperatures were not constant during the measuring period, it is difficult to verify this hypothesis by analysing the measured data, as outdoor temperature is one of the main driving factors for opening windows during warm weather [25, 35-36].

Symptom intensity was higher in the classroom with a mechanical ventilation system in both the heating and the non-heating season, suggesting that it may have a common cause in both periods. It could be a result of higher pollution levels in this classroom, as mentioned above. The pupils judged the air to be less fresh in this classroom even though the ventilation rates were higher and the CO_2 levels were lower than in the other classrooms, which supports this explanation. Another reason for this unexpected result could be the sample of children participating in the present experiments. Pupils from the 8th and 9th grade reported their symptoms and perceptions in the classroom with a mechanical ventilation system, while all other classrooms were evaluated by 4thand 5th grade children. The difference in syllabus and the form of teaching could contribute to reported levels of fatigue and a reduced willingness to perform schoolwork in the classroom with a mechanical ventilation system. Age difference could also be a factor, as teenagers tend to be more critical and disapproving than 11-12-year-olds. The lack of correlation between the symptoms and the measured classroom temperatures and CO_2 levels supports this speculation. The limitation of the present study was that different groups of children judged the conditions in classrooms with different ventilation type. Differences between groups of pupils exposed in different classrooms (on average about 20 pupils participated in each class) could obscure the results and made the statistical tests less sensitive. Future experiments should ideally ensure that the same pupils are repeatedly exposed in the same classroom with different ventilation systems.

Pupils indicated that the classrooms with either a mechanical ventilation system or automatically operated windows with an exhaust fan were noisier in both the heating and the non-heating season. It may be that some of the symptoms reported by pupils in the classroom with mechanical ventilation can be attributed to noise. Unfortunately, no noise measurements were made and it was not possible to correlate noise levels with symptoms, nor was it possible to compare the actual noise levels in different classrooms. On the other hand, the fact that perceptions and symptom intensity were generally lower in the classroom with automatically operable windows and exhaust fan than in other classrooms means that it is not likely that noise played an important role in the exacerbation of symptoms in the mechanically ventilated classroom. In the case of the classroom with automatically operable windows the source of noise could be of a different kind and origin (ambient noise when windows were open), whereas in the mechanically ventilated classroom most of the noise will have been generated by the mechanical ventilation system.

Based on the results of the present measurements, mechanical ventilation and natural ventilation with automatically operable windows in which adequate natural ventilation is assured (e.g. by cross ventilation or by installation of an exhaust fan) can be recommended in classrooms. The measurements show that the performance of these systems was notably better than in the classrooms where windows had to be opened manually for airing or where windows were opened automatically but with no means of ensuring that this would provide adequate ventilation (exhaust fan idled). The strength of the present measurements is that they were performed for a relatively long time (1 month) in two different seasons, so the results are applicable to the entire school year. The present results have not clearly determined which of the two preferred systems is better. It will depend on the school location, climate conditions and many other factors. The two most important selection criteria are energy use and the need for conditions that do not have a negative effect on learning. Neither energy use nor progress in learning was simulated or measured in the present experiments so they should be addressed in future studies. From the results presented in Table 2 and Figure 7 it was estimated that the 1°C lower average temperatures in the non-heating season and twice as high ventilation rates in the heating season that automatically operated windows achieved, in comparison with manually operated windows, would affect the performance of typical schoolwork by 4% and 14% respectively [5]. The size of these expected effects is so high that they simply cannot be dismissed as irrelevant. Future studies should verify these estimates experimentally. They should also include measurements and modelling of energy use in classrooms with different ventilation systems, including cases where energy recovery is in operation. Although energy was not measured in the present work, as it was not the main object of the study, it is clear that classrooms with a mechanical ventilation system would have the lowest energy use if effective heat recovery systems were installed [19]. However, in model studies, Steiger et al. found quite a large reduction in energy use in classrooms with hybrid ventilation compared with the mechanical ventilation system [37]. Their simulation showed that the energy used in schools with natural and mechanical ventilation was similar (18-21 kWh/m^2 per year), while it was up to 52% lower in a school with hybrid ventilation (9-10 kWh/m^2 per year). These results must be validated by performing actual measurements in occupied schools, as they may not have correctly modeled pupils' window opening behavior.

The present study was performed in a suburban area where the annual and daily levels of airborne particles are generally lower than the levels recommended by the World Health Organization, respectively 10 and 25 µg/m^3 for PM2,5 and 20 and 50 µg/m^3 for PM10 [38-39]. The ambient pollution levels did not place any restriction on the use of natural ventilation systems with manually or automatically operated windows. In places where the ambient pollution does not meet the levels recommended by the WHO, some means of filtration and air cleaning must be applied before the air can be admitted indoors [40-41].

5. Conclusions

- The mechanical ventilation system was able to ensure the highest outdoor air supply rates in the classroom, independently of the season, although the perceptions and symptoms reported by pupils were not more favourable. Classroom with automatically operable windows and an exhaust fan that ensured adequate ventilation at all times performed better in this respect, estimated ventilation rates being only slightly lower than the current requirements of the Danish Building Code and the CO_2 levels being generally below 1,000 ppm.
- Pupils opened the windows regardless of the type of ventilation, which indicates that this behaviour is more a function of habit. Outdoor conditions were also an important determinant of window opening behaviour. Windows were opened less frequently or not at all during winter (in the heating season). In contrast they were opened more often (nearly all the time) during warm weather (in the non-heating season).
- Based on the present results, hybrid ventilation systems seem to be a possible solution for ventilation in schools located in temperate zones, but only when the ambient air pollution is sufficiently low, when ambient noise levels are low, and when energy recovery systems are installed. Further studies should investigate the impact of these three aspects more deeply, as they were not the main objective of the present work. They should also examine whether there are any negative effects on learning.
- The present results provide the basis for a rational selection of systems that ensure adequate classroom ventilation and acceptable indoor environmental quality throughout the entire school year.

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