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Use of CO_2 feedback as a retrofit solution for improving air quality in naturally ventilated classrooms

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SUMMARY
Carbon dioxide (CO_2) sensors that provide a green/yellow/red visual indication were installed in pairs of naturally ventilated classrooms during normal school operation. During a two-week period in the heating and the cooling season, teachers and students were instructed to open the windows in response to the CO_2 feedback in one week and open them as they would normally do, without feedback, in the other week. In the cooling season, two pairs of classrooms were monitored, one pair with split cooling in operation and the other pair with no cooling. The resulting indoor environmental conditions in these classrooms and window opening behaviour were monitored. Children also reported their perceptions and symptoms. Resulting energy use was measured and used to estimate annual energy use. Providing CO_2 feedback reduced CO_2 levels. More windows were opened in this condition, and this increased energy use for heating and reduced the cooling requirement. Split-cooling reduced the frequency of window opening when no CO_2 feedback was present, suggesting that classroom temperature is the driving factor for this behavioural response. Children liked CO_2 feedback; their perceptions and symptoms were somewhat improved with CO_2 feedback, although many of these changes did not reach formal statistical significance.

KEYWORDS
Schools; Classrooms; Carbon dioxide; Ventilation; Retrofit solution; Energy

1 INTRODUCTION

Many studies have shown that the environmental conditions in elementary schools are often inadequate. The most common problems in schools are insufficient outside air supplied to occupied spaces; 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 main reasons for this situation are inadequate financial resources for the maintenance and upgrade of school buildings, and an overemphasis on energy conservation. Consequently, classroom temperatures are allowed to drift above the recommended range of 20-22°C in warm weather and outdoor air supply rates are allowed to remain so low that carbon dioxide (CO_2) levels regularly exceed 1000 ppm during school hours, i.e. that energy conservation is allowed to create conditions that are worse than what is stipulated by the relevant standards and building codes.

Children are quite vulnerable to environmental impacts, and 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 lowering the performance of typical schoolwork, the academic achievements of children and increasing absenteeism (Haverinen-Shaughnessy et al., 2010; Shendell et al., 2004; Wargocki and Wyon, 2006). It is therefore essential that environmental conditions in classrooms are such that they promote rather than hinder learning and avoid negative consequences for the proper development of young people, in order to avoid potentially negative impacts on future generations and an increase in societal and economic costs (Chetty et al., 2010).

Many existing schools are naturally ventilated. These schools often need to be retrofitted with systems that ensure adequate air quality and temperature if they are to achieve improved indoor environmental quality in classrooms. This may be quite expensive, not only because of the potentially high first costs of retrofits but also due to the often increased energy and maintenance costs incurred when systems that ensure high classroom quality are in operation. Retrofitting the existing building stock may take many years to complete. Simple retrofit solutions are therefore needed. 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 feedback to pupils on CO_2 levels in classrooms and thus indicating when the windows in the classroom should be opened. The goal was to determine whether opening windows in naturally ventilated classrooms in response to CO_2 feedback would improve classroom air quality, the consequences for the perceptions and symptoms reported by pupils and the effects on energy use.

2 METHODS

Field experiments were carried out in pairs of identical classrooms in an elementary public school located in a small coastal town north of Copenhagen. The experiments were carried out during normal school operation in 4th and the 6th grade classrooms (in which the children were 10-12 years old). The classrooms have large glazed south-facing facades with operable windows. Each classroom has a floor area of 50 m^2 plus 15 m^2 of entrance hall and a volume of 187.5 m^3. There are on average 23-24 pupils in each class. The classrooms are heated by water radiators with thermostatic valves, located under the windows. They can be aired out by teachers and students by opening any of the 5 operable windows, together with opening of main doors to achieve cross-ventilation. In two of the classrooms selected for the experiments split-cooling units with barely-audible air-circulation fans had been installed for a previous field experiment; they are normally switched off and operated only occasionally during very hot periods in late spring or summer.

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 one of each pair of classrooms for one week, then moved to the other classroom in the pair, in a crossover design that was capable of balancing any effects of order of presentation and robust to external factors such as weather. Green diodes indicated CO_2 levels below 1,000 ppm, yellow the range from 1,000 to 1,600 ppm and red the levels above 1,600 ppm. During two-week periods in the heating season (March-April 2011) and the cooling season (June 2011) teachers and students were instructed to open the windows in response to the feedback during the week it was present and to open them as they would normally do when the feedback was not present. They were instructed to open the windows proportionally, i.e. not all windows at once, but one by one as an increasing number of yellow lights were lit. When the lights were red they were told to open all windows and the main door, to achieve intensive cross-ventilation and also to leave the classroom for a short while to allow the CO_2 level to drop. Each condition was maintained for one week. During the cooling season, two pairs of classrooms were examined, one pair with split cooling and another pair without. A cross-over design was not used, so each of these 4 classroom either had no feedback for two weeks or feedback for both experimental weeks. This makes it possible to examine classroom behaviour over two school weeks. During the experiments no changes in the schedule of normal school activities were made, in order to ensure that the teaching environment and routines were as normal as possible. No indication of classroom or outdoor temperature was present in any of the classrooms.

The classroom temperature, relative humidity and CO_2 were continuously monitored together with continuous logging of outdoor conditions, using a weather station located on the roof. Miniature event loggers recorded when each window was opened and for how long. Energy use was monitored during the heating season by installing electronic metering devices for recording the heat consumption on the water-filled radiators. The thermostatic valves were set to one position during these measurements, and the thermostatic control of the split-cooling units, when in operation, was set to 22°C. On Thursday of each week, towards the end of the school day, children reported their perceptions and symptoms using a paper questionnaire that was distributed by the teachers. Different questions were answered (Table 1) on a visual-analogue type of scale where the line was replaced by a set of "smiley's" to make it easier for children to indicate their response (Figure 1). 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. Annual energy use was estimated from the measured values in a simulation using IDA-ICE 4, in which window opening behaviour in the condition with CO_2 feedback was assumed to take place according to the instructions given to the children and the teachers. In the condition without feedback window opening was simulated to match actual CO_2 levels measured in the classrooms and to maintain the set points for classroom temperature. An adjustment was also made so that the relative difference in energy use for heating between the conditions matched the ratio between energy use as measured by the meters installed in the classrooms in each condition.

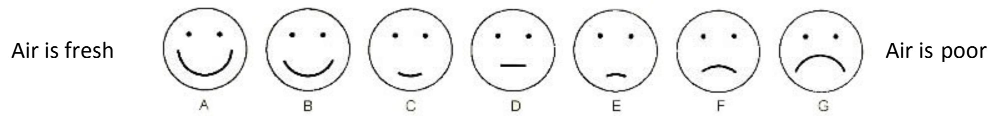

Figure 1. An example of a scale used to obtain the perceptions and symptoms of pupils. The scale was coded as follows: A=7, B=6, C=5, D=4, E=3, F=2 and G=1.

3 RESULTS

Figure 2 shows how providing CO_2 feedback affected the opening of windows and the conditions in the classrooms.

In the heating season, with outdoor temperatures of 6 to 12°C, children opened the windows more frequently when feedback was present. This resulted in CO_2 levels in the classroom at or below 1,000 ppm, the level at which children were instructed to open the windows. The CO_2 levels without feedback were as high as 1,400 to 1,800 ppm. Classroom temperatures were not affected by more frequent opening of windows.

In the cooling season, the outdoor temperatures were 18 to 22°C. There was no difference in window opening behaviour when feedback was provided in the classrooms without cooling, except for the early morning hours when the CO_2 levels in the classrooms without feedback were slightly elevated. 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°C independently of whether CO_2 feedback was present or not. However, in these classrooms the windows were opened less frequently when there was no feedback, leading to slightly elevated CO_2 levels of about 1,200 ppm.

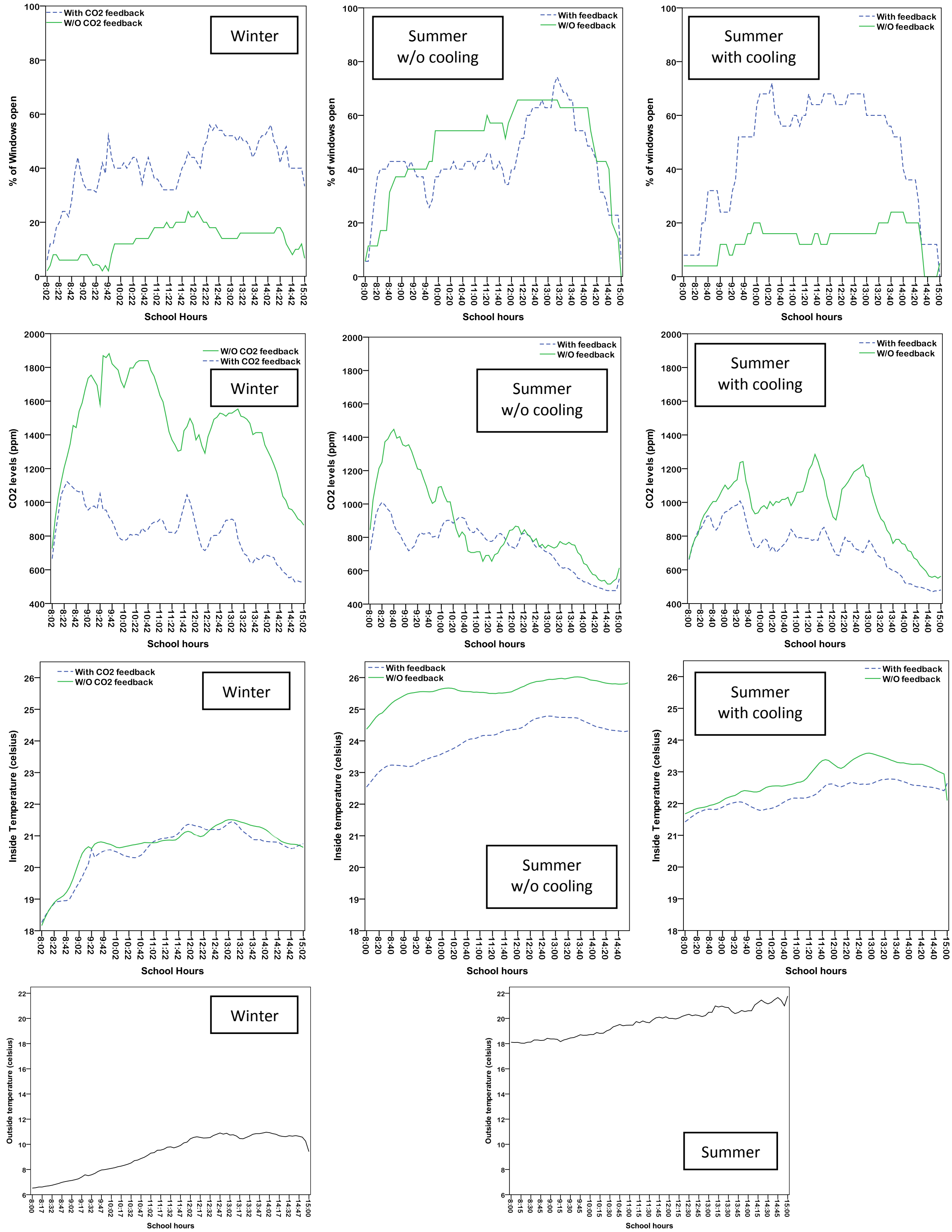

Figure 2. Time-weighted average of % windows opening, CO_2 concentrations and classroom temperature during school hours with and without CO_2 feedback; the last row shows the time weighted average values of the outdoor temperatures registered during the experiments

Children very much liked to use the CO_2 feedback, both as reported using the scale with smiley's and in personal communication with the experimenters. Installing CO_2 feedback had very little effect on the perceptions and symptoms indicated by pupils, only a few differences reaching statistical significance (Table 1). Simulations of energy use showed that heating demand was on average 10-20% higher, and the cooling demand 10 to 25% lower, in classrooms with CO_2 feedback compared with classrooms without CO_2 feedback.

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

	Heating Season (winter)			Cooling Season (with split cooling)			Cooling Season (w/o split cooling)		
	With CO_2 feedback (n=43)	w/o CO_2 feedback (n=43)	P (wilcoxon)	With CO_2 feedback (n=23)	w/o CO_2 feedback (n=21)	P (Mann-Whitney)	With CO_2 feedback (n=47)	w/o CO_2 feedback (n=46)	P (Mann-Whithney)
How was the classroom environment during the week?									
Very Good (7)-Very Bad (1)	6 [5-6,5]	6 [5-6,5]	0,75	6 [5-6]	6 [6-7]	0,18	5,5 [5-6]	5 [3-5]	0,001*
How was the classroom this week?									
Too cold (7)-Too warm (1)	4 [4-5]	4 [3-5]	0,35	4 [3-5]	5 [4-5]	0,15	4 [3-4]	2 [2-3]	<0.001*
Air was fresh (7)-was poor (1)	5 [4,5-6]	5 [4-6]	0,15	5 [5-6]	6 [5-6]	0,2	5 [3-5]	3 [2-4]	0,001*
Air was still (7)–was drafty (1)	5 [4-6]	6 [4,5-6,5]	0,19	6 [5-7]	6 [5-7]	0,41	6 [5-7]	4 [3-5]	<0.001*
Too much noise (7)-Too silent (1)	5 [4-5]	5 [4-5]	0,27	5 [5-6]	4 [4-4]	0,001	4 [4-5]	4 [3-4]	0,03*
Too Humid (7)-Too dry (1)	4 [4-4]	4 [4-4]	0,84	4 [4-5]	4 [4-4]	0,72	4 [4-4]	4 [3-4]	0,02*
Too much (7)-Too little (1) light	4 [4-4,5]	4 [3-5]	0,22	4 [4-4]	4 [4-5]	0,22	4 [4-5]	4 [3-4]	0,2
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	6 [5-7]	6 [6-7]	0,21	6 [4-6]	4 [3-5]	0,001*
Not tired (7)-Felt very tired (1)	5 [4-6]	5 [3-6]	0,18	5 [4-6]	5 [3-6]	0,8	4 [3-6]	3 [2-5]	0,2
No headache (7)-severe headache (1)	6 [5-7]	6 [3,5-7]	0,23	6 [5-7]	6 [5-7]	0,6	5,5 [4-7]	4 [2-7]	0,06
Felt (7)-felt not (1) like working	6 [5-6]	5 [4-6]	0,02*	6 [5-6]	6 [4-6]	0,88	6 [5-6]	4,5 [4-5]	0,005*
Not dry lips (7)-dry lips (1)	6 [4-7]	5 [4-7]	0,12	6 [5-7]	6 [2-6]	0,23	6 [4-7]	5 [3-7]	0,15
Not dry skin (7)-dry skin (1)	6 [4-7]	5 [4-7]	0,79	7 [6-7]	6 [4-7]	0,21	6 [5-7]	3 [6-7]	0,1
Not dry throat (7)-dry Throat (1)	6 [5-7]	6 [4-7]	0,05*	6 [5-7]	6 [4-7]	0,71	6 [5-7]	5 [3-7]	0,11
Felt good (7)-not felt good (1)	7 [6-7]	6 [5-7]	0,02*	6 [6-7]	7 [5-7]	0,9	6 [5-7]	6 [3-7]	0,29

4 DISCUSSION

As expected, providing pupils with a visual signal that indicated when the windows should be opened reduced the levels of classroom CO_2 and improved classroom air quality. These results were all obtained in one school, located in a rural area with relatively good ambient air quality. It may be unsafe to generalise these results to urban schools with noisy ambient environments and polluted ambient air. However, it is worth noting that a similarly positive effect of reduced classroom CO_2 levels was obtained in a large number of Dutch schools when CO_2 indicators were installed (Geelen et al., 2008). The experiments in the heating season were performed 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 and fluctuating temperatures. This may not be the case when outdoor temperatures are lower than those in the present experiments and therefore the results cannot be generalised to colder outdoor conditions until more evidence is available.

In classrooms with cooling windows were opened less frequently when no CO_2 feedback was installed. This may suggest 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. This would be consistent with what was observed in classrooms without cooling, where windows were opened just as frequently whether CO_2 feedback was present or not.

As in several previously reported experiments (Wargocki and Wyon, 2006) the perceptions and symptoms of pupils were hardly affected by the improved air quality that resulted from more frequent window opening, even though this time “smiley’s” instead of the linear scale were used. This may still be because children this age may have difficulty in interpreting the scales, or that interventions should last longer than the one or two weeks of this and the previous experiments, or that a larger group of children should be studied. In future experiments other means than the subjective intensity scales (e.g. physiological measurements) or other subjective scales should perhaps be used to collect information on the perceptions and symptoms experienced by pupils.

The energy simulations show that installing CO_2 feedback is quite beneficial, especially in the cooling season when cooling demands were reduced as a result of frequent window opening; these results are valid for climates similar to Danish as these were the conditions used in simulations. The limitation of the simulations is that they do not reflect the actual window opening behaviour of children, e.g. the simulations assumed that windows would always be closed when CO_2 levels were below 1,000 ppm, and this may not be the case in practice.

Future studies should examine whether providing a visual signal causes any distraction from schoolwork and thus has a negative effect on school performance and progress in teaching, and whether children continue to open the windows using the feedback over longer periods than the two weeks examined in the present experiments.

5 CONCLUSIONS

Despite its limitations, 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 fairly mild.

Classroom temperature seems to be the main factor affecting window opening. 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.

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