Ventilation, indoor air quality and learning in schools

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ABSTRACT

Studies show that environmental conditions in schools are often inadequate, even in developed countries, and that they are frequently much worse than in office buildings. Outdoor air supply rates in schools are considerably lower than in offices, in many cases even lower than those observed in dwellings. Research studies show that inadequate classroom ventilation can reduce learning abilities of pupils in elementary school as measured in form of improved performance of typical school tasks requiring skills in maths and language and in form of the tests used by educational departments to examine the progress in teaching. Inadequate ventilation rates will also decrease illness absence, which may be detrimental for learning process. Children in classrooms with poor ventilation are less attentive and less concentrated. The negative results on learning may have significant economic implications, which are not immediate and can be first harnessed in the future when children join the job market, but some of them may be also seen immediately in form of the reduced absence rate of teachers as well as parents or caregivers. The ventilation solutions to improve classroom ventilation will largely depend on the climatic conditions but in the case of moderate climates mechanical ventilation and hybrid systems seem the most attractive solutions.

KEYWORDS

Elementary schools; indoor air quality; ventilation; learning

1 INDOOR AIR QUALITY AND VENTILATION IN SCHOOLS

Studies show that the environmental conditions in schools are often inadequate, even in developed countries, and that they are frequently much worse than in office buildings. For example, measurements in 39 schools in Sweden showed that 77% of schools did not meet building code regulations (Smedje and Norbäck, 2000). The most common defects in schools include insufficient outside air supplied to occupied spaces; water leaks; inadequate exhaust air flows, poor air distribution or balance; and poor maintenance of heating, ventilation and air-conditioning (HVAC) systems, as indicated by the analysis of 88 National Institute of Occupational Safety and Health (NIOSH) Health Hazard Evaluation Reports for educational facilities in the USA where formal complaints had been registered (Angell and Daisey, 1997; Daisey et al., 2003).

Outdoor air supply rates in schools are considerably lower than in offices, in many cases even lower than those observed in dwellings (Brelih, 2012; Dimitroulopoulou, 2012). They are also often much lower than they should be according to current recommendations for classrooms (Daisey et al., 2003, Dijken et al, 2005). For example, ASHRAE Standard 62.1 (2014) recommends for classrooms 5 L/s per person plus 0.6-0.9 L/s per m^2floor. Low ventilation rates often lead to carbon dioxide (CO_2) levels being well above the recommended level of 800-1,000 ppm (sometimes 1,400 ppm) during school hours (Sowa, 2002; Dijken et al., 2005; Boxem et al., 2006; Santamouris et al., 2008; Wyon et al., 2010; Gao et al., 2014), implying that the concentration of other pollutants, not only the bioeffluents from children for which CO_2 is a good indicator, will be high, and that classroom air quality is consequently poor.

In recent air quality measurements in 320 schools in Denmark, CO_2 concentrations exceeded 1,000 ppm in more than 50% of classrooms (Menå and Larsen, 2010, Clausen et al., 2014; Toftum et al., 2015). The air quality in these classrooms did not meet the requirements of the Danish Building Code nor the Danish Working Environment Authority because the outdoor ventilation rates were too low. For comparison, similar measurements in Norway and Sweden showed that only in no more than 20% of classrooms were the CO_2 concentrations above 1,000 ppm. Many studies have also reported high concentrations of particles in classrooms (e.g., EFA, 2001; Dijken et al., 2005; Simoni et al., 2010).

2 EFFECTS ON LEARNING

Majority of studies examining the effects of indoor air quality and ventilation on the performance of schoolwork and learning used psychological and neurobehavioral tests. These tests examine different skills needed for proper learning, such as the ability to concentrate and memorize (Myhrvold et al. 1997; Bako-Biro et al. 2010; Ribic 2008). They used also shorter tests examining the ability to read, comprehend and calculate (Wargocki and Wyon 2013). For example, a classroom study by Myhrvold et al. (1996) found a weak association between CO_2 levels and simple reaction time suggesting a positive effect of increased ventilation on performance. In studies reported by Wargocki and Wyon (2013) pupils performed arithmetical calculations and language based tasks under different conditions of air quality achieved by changing ventilation rate between 3 and about 10 L/s per person (Figure 1). The speed at which the tasks were solved was improved with increased ventilation, but there were no effects on errors. Similar results were observed by a recent study, which copied the experimental approach of Wargocki and Wyon (Petersen et al., 2015). Also in a study of Bako-Biro et al. (2010), the performance of range of cognitive tasks was improved as well as time needed to solve simple math tests was reduced when ventilation rate was increased from about 0.3-0.5 to 13-16 L/s per person. Ribic (2008) observed improved performance on d2-test, a standard test for measuring concentration, when CO_2 concentration was reduced from around 3,800 to 870 ppm (absolute level). In contrast to these observations, Mattsson and Hygge (2005) did not observe any positive effect of operation of particle air cleaners on psychological tests despite the measureable effect on classroom levels of particles.

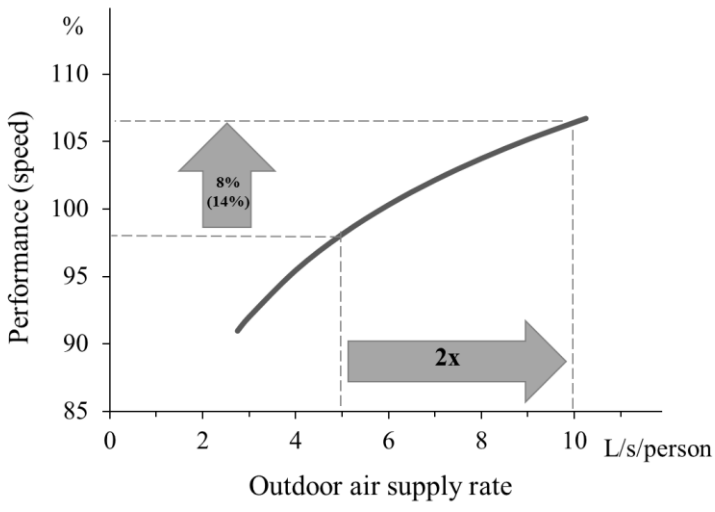

Figure 1: Performance of math and language-based tasks under different levels of outdoor air ventilation rates (Wargocki and Wyon, 2013)

Although the long-term learning outcomes are expected to be affected by the absence of abilities to perform simple psychological tests and ability to read, calculate and comprehend, the connection between the progress in learning and these abilities is not very well documented. Therefore, some studies monitored long-term learning using standardized tests, which are often developed by national education departments. These tests monitor the progress in learning and benchmark both individual pupils and schools, as well as evaluate the effectiveness of teaching methods and curricula over time. Haverinen-Shaughnessy et al. (2011) showed that poor ventilation in classrooms reduced the number of pupils just passing language and math tests (Figure 2). In another study by Toftum et al. (2015), academic achievement was evaluated with the scores from a standardized Danish test scheme, adjusted for a socioeconomic reference score. The lowest national test scores were generally found for pupils in classes with CO_2 concentrations above 2,000 ppm, although the association was not significant. Pupils in schools with some means of mechanical ventilation scored on average higher in the national tests than pupils in schools with natural ventilation, probably because the efficacy of ventilation was higher.

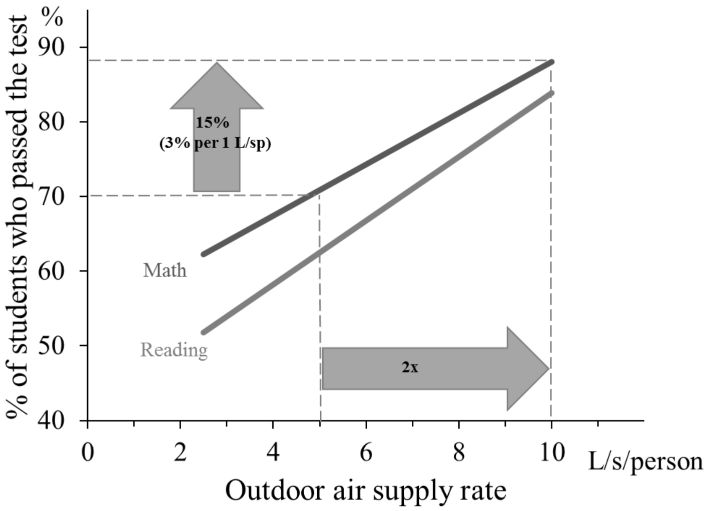

Figure 2: Performance of standard tests examining progress in math and language proficiency at different rates of ventilation with outdoor air (Haverinen-Shaughnessy et al., 2011)

The results from the previous experiments on the effects of classroom air quality on the performance of schoolwork do confirm that these effects are systematic and suggest that improving classroom air quality will have significant positive effect on some aspects of learning, both on cognitive skills and academic attainment, as well as on academic achievements. The level of this effect is not the same across different studies as might be expected but with reasonable confidence it can be assumed that doubling ventilation rate would improve the performance of schoolwork by up to 14% and each additional 1 L/s per person would increase number of students passing the tests by 3% and would reduce the absence rates by at least 1.6% (Figures 1-2).

Some studies measured illness absence and associated it with poor air quality or poor classroom ventilation to examine indirectly the effects on learning outcomes. Pilotto et al. (1997) showed in a cohort study that air pollutants from gas heaters had a negative effect on attendance at school, which was presumed to be due the result of negative effect on children’s health. Berner (1993) showed an association between poor maintenance of schools and the poor academic achievement of the children attending them. Ervasti et al. (2012) found increased short-term sick leave among teachers in schools with poorly perceived air quality, while Simons et al. (2010) found high student absenteeism to be associated with poor ventilation in 2751 New York schools. Shendell et al. (2004) found student absence to decrease by 10-20% when CO_2 concentration decreased by 1,000 ppm in 434 American classrooms. However recent study of Gaihre et al. (2014) in Scottish schools showed that an increase of 100 ppm of CO_2 corresponds only to 0.2% increase in absence rates (roughly one order of magnitude lower than the data of Shendell et al. (2004)) corresponding to about 0.5 day a year in a 190–days long school year. The study of Gaihre et al. (2014) did not however find any relationship between air quality approximated by the levels of CO_2 and educational attainment measured as the percentage of class attaining the average level expected for this group. Another recent and very comprehensive study in 162 Californian classrooms observed that illness absence decreased by as much as 1.6% for each additional 1 L/s per person (Mendell et al., 2013); this is again lower than the data of Shendell et al. but higher than the data of Gaihre et al. Finally a recent work, though performed in day care centres equipped with the balanced mechanical ventilation system, found that increasing air change rate by 1 h^{-1} would reduce the number of sick days by 12% (Kolarik et al., 2015); these results were observed even though the ventilation rates were quite high in these day-care centres (CO_2 levels were <1,000 ppm, and on average around 640 ppm). The above findings suggest that increasing classroom ventilation may substantially decrease illness absence and may affect the learning experience though it is not clear whether or to which extent the short-term absence of pupils would affect academic performance (Mendell and Heath, 2005).

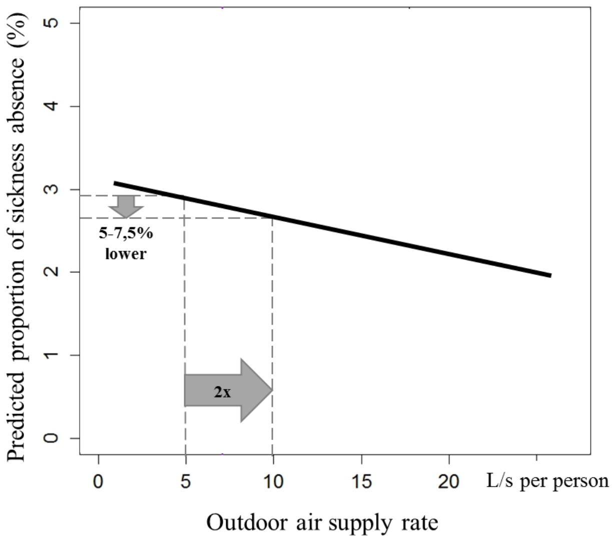

Figure 3: Absence rate as a function of carbon dioxide concentration (ventilation rate) in different school districts in California (Mendell et al., 2013)

3 ECONOMIC IMPLICATIONS

Wargocki et al. (2014) attempted to estimate future socio-economic consequences of improved indoor air quality in Danish primary schools. Assuming that increased school performance will improve productivity, will reduce the duration of primary education (in Danish system the pupil can take either 9 or 10 grades in the elementary education depending on the educational attainment) and absenteeism of teachers, the macro-economic effects were estimated of increasing ventilation rates from 6 L/s per person required by the Danish Building Code to 8.4 L/s per person required by the Swedish Code. Modelling of benefits showed that increasing ventilation would yield an average annual increase in GDP of €173 million due to increased productivity of the workforce and more pupils leaving the school earlier, and an average annual increase in the public budget of €37 million again through improved productivity and shorter stay in primary school as well as lower teacher sick leave. These effects correspond to no more than 0.07% of Danish GDP in 2011 thus seems reasonable in magnitude. All effects are expected to increase (being higher and higher from year to year over the 20 years for which the analyses were performed) the more students leave the schools where the air quality and ventilation are improved.

A different estimation of the effects of reduced absence rates was performed by Mendell et al. (2014). They assumed that ventilation rates in Californian K-12 schools will be increased from current level of 4 to 7.1 and 9.4 L/s per person, and estimated the benefits from decreased illness absence to school districts (i.e., increased revenue from the State for student attendance which is the model adopted by the schooling system there), and the benefits to families as a result of decreased costs from lost caregiver wages/time. These benefits yielded from US$33 to US$66 million from increased revenue and from US$80 to US$160 million from reduced losses to caregivers.

Both estimations show that the benefits and potential losses due to reduced learning ability because of poor air quality could be considerable and although not providing immediate tangible benefits (except the effects on absence rates) they should not be neglected.

4 POSSIBLE VENTILATION SOLUTIONS

Gao et al. (2014) examined how different types of ventilation systems influence classroom temperature and air quality, and whether there is any impact on window opening behaviour of pupils and teachers. The classrooms were selected in the same school located in rural Copenhagen with different methods of ventilation obtained as follows: by manually operable windows, by automatically operable windows with and without exhaust fan, and by balanced mechanical ventilation system. Measurements were performed for one month in the selected classrooms during non-heating season when outdoor temperatures were 10-30℃ (during school hours) and in the heating season when outdoor temperatures were when the outdoor temperatures ranging from -7.3 to 10.9℃. The results showed that classrooms with automatically operable windows and exhaust fan and with mechanical ventilation systems achieved the best thermal environment and air quality during both heating and non-heating season among all classrooms examined, while classroom with manually operable windows had the highest carbon dioxide concentration levels more so during heating season (Figure 4). These results may suggest that hybrid ventilation and mechanical ventilation system are the most feasible solutions for moderate climates typical for Denmark. These results should not be generalized for other climates such as e.g. cold or Tropical climates without providing sufficient research evidence.

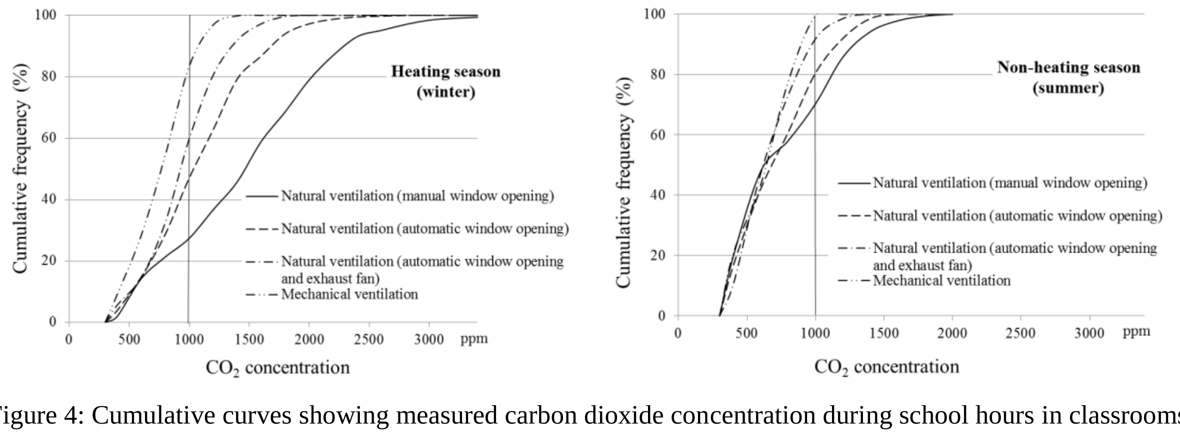

Figure 4: Cumulative curves showing measured carbon dioxide concentration during school hours in classrooms with different ventilation systems during heating and non-heating season (Gao et al., 2014)

Wargocki and da Silva (2015) examined whether providing pupils in elementary school with visual feedback on the classroom concentration of CO_2 and instructing them to open the windows in response to this indication would results in changes in window opening behaviour and in improved classroom ventilation. The study was performed in the heating and non-heating season, in the latter case with and without split air-conditioner securing classroom temperature at comfortable level. During a two-week periods in both seasons, 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. Providing CO_2 feedback caused that more windows were opened in this condition, as expected and reduced CO_2 levels (Figure 5). 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. Despite many limitations, da Silva et al. recommended the use of CO_2 feedback as a feasible solution for controlling classroom air quality in rural schools with natural ventilation when ambient climate conditions are mild. The Authors cautioned that cooling of naturally ventilated classrooms may reduce window opening and therefore will result in poor classroom air quality.

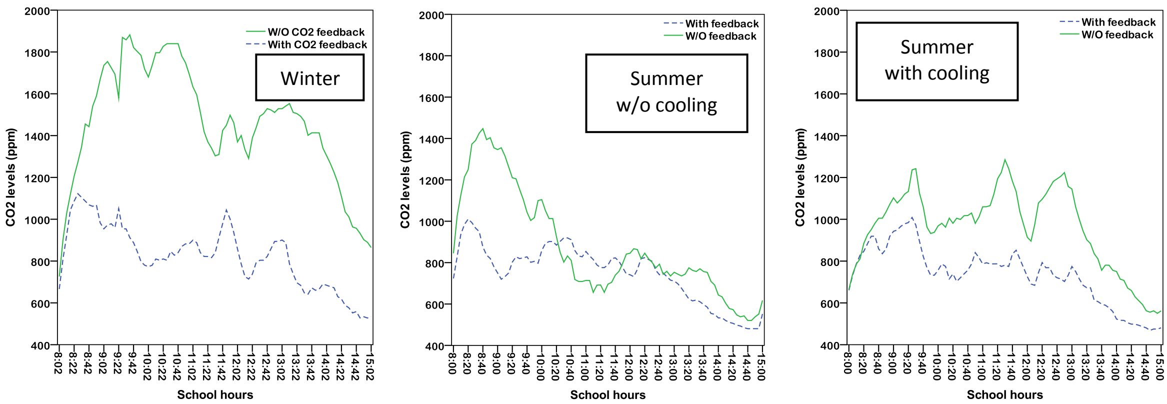

Figure 5: Carbon dioxide concentration in classrooms during school hours when pupils were able and not able to use visual feedback; measurements are shown for heating season and non-heating season, in the latter case for two instances when the temperature in the classroom was not controlled and could drift according to the temperature outdoors and when it was controlled with split cooling unit to avoid thermal discomfort (Wargocki and da Silva, 2015)

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