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Providing better thermal and air quality conditions in school classrooms would be cost-effective

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ABSTRACT

This paper is an overall summary of research by the authors on how classroom conditions affect the performance of schoolwork by children, motivated by the fact that the thermal and air quality conditions in school classrooms are now almost universally worse than the relevant standards and building codes stipulate that they should be. This is sometimes because financial resources for the maintenance and upgrade of school buildings are inadequate, but it is also because schools are increasingly allowing classroom temperatures to drift above the recommended range of 20–22 °C in warm weather and allowing outdoor air supply rates to remain so low that carbon dioxide (CO_2) levels during school hours exceed 1000 ppm for long periods, in order to conserve energy. The research that is summarized in this paper shows that the indoor environmental consequences of either of these investment-free but ill-advised energy conservation measures can reduce children's performance of schoolwork by as much as 30%, so a more sophisticated approach to maintaining good classroom indoor environmental quality (IEQ) is required.

1. Introduction

The environmental conditions in elementary schools are often inadequate, even in developed countries, and 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 [1], and a series of measurements in a structured representative random sample of 100 schools in Denmark during the autumn of 2009 [2] found that the average carbon dioxide (CO_2) concentration during school hours was above 1000 ppm, the maximum level recommended by the school authorities, for 56% of school hours. According to an analysis of 88 National Institute of Occupational Safety and Health (NIOSH) Health Hazard Evaluation Reports for educational facilities in the USA against which formal complaints had been registered [3], the most common defects in schools include insufficient outside air supplied to occupied spaces and inadequate exhaust air flows. Outdoor air supply rates per person in classrooms are often much lower than they should be according to current recommendations for classrooms [3,4]. Shendell et al. [5] found that, in 50% of the 434 classrooms they studied in 22 schools, the outdoor air supply (OAS) rate was below the minimum recommended by ASHRAE (15 cfm per person), which is only 7 L/s/p: many European countries recommend a minimum OAS of 10 L/s/p. Santamouris et al. [6] performed a meta-analysis of reported CO_2 levels in classrooms worldwide and found that the median level in naturally-ventilated schools was 1410 ppm (versus 910 ppm in mechanically ventilated schools). Elevated CO_2 levels indicate low ventilation rates [4,7,8] and thus elevated concentration of other pollutants and the bio-effluents from children, leading to poor classroom air quality. Classrooms have also been reported to have high concentrations of airborne particles [4,9,10].

In addition to poor air quality, classrooms often provide unsuitably high temperatures, even in cold countries. For example, a 1967 survey of temperatures in a large number of schools in Sweden showed that classroom temperatures were generally 23–25 °C in the shoulder seasons (April to September), which was 3–6 °C above what teachers and pupils preferred, while some classroom temperatures were as high as 30 °C [11]. The most common reason for such high temperatures was that classroom ventilation rates were too low to remove the excess heat load caused by sunshine entering the windows, which had at that time been designed to provide as much daylight as possible, i.e. with large glazed areas that faced the sun. In naturally-ventilated schools, windows must often remain closed to exclude external noise and prevent draughts, but unsuitably high temperatures may

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also occur in schools with mechanical ventilation when they have no cooling. Unsuitably high indoor temperatures have been observed in low-energy housing in Denmark [12], due to their high insulation values, and as future schools may be designed to be low-energy or near-zero-energy buildings, unsuitably high temperatures in classrooms may become even more common.

Children must attend schools even when the air quality and thermal conditions in the classrooms are unsuitable, because they cannot easily choose to attend another school and they have fewer ways of registering complaints than adults have. The work that children are obliged to perform in school is almost always new to them, while adults frequently perform routine, well-practiced tasks. It is therefore surprising that up to 2005 so little research had even attempted to discover whether the performance of schoolwork by children is affected by poor air quality and by elevated temperatures in classrooms [13], although Myhrvold et al. [14] had found a weak association between CO_2 levels and simple reaction time, with a correlation coefficient of 0.11, suggesting a positive effect of increased ventilation on performance, Shendell et al. [5] had shown that higher ventilation rates were associated with lower absence rates in elementary schools and Berner [15] had shown an association between poor maintenance of schools and the poor academic achievement of the children attending them. Bakó-Biró et al. [16] showed that increasing the ventilation rate in classrooms improved the performance of pen-and-paper school tasks that required mathematical and language skills, and improved the results obtained in a range of computer-based psychological diagnostic tests, while Haverinen-Shaughnessy et al. [17] showed that in classrooms with high ventilation rates, as indicated by a lower concentration of CO_2, a higher proportion of pupils passed the standard language and mathematical tests that were routinely applied by the educational department. The only study that directly tested whether reducing particle concentrations in classrooms would improve the performance of schoolwork found that even though the electrostatic air cleaners that were experimentally installed did reduce the concentration of airborne particles, there was no general effect on the performance of schoolwork [18].

A number of previous studies of the effects of temperature on the performance of schoolwork suggest that thermal conditions are important for the proper educational development of children. However, they were all obtained nearly four decades ago, and they yield little information on how far below the higher end of range of temperatures examined in these experiments it is possible to extrapolate the findings.

Schoer and Shaffran [19] reported three experiments in which 10–12-year old pupils in matched pairs were assigned either to a classroom without cooling (where the temperature was about 26 °C), or to an adjacent air-conditioned classroom (where the temperature was about 22.5 °C). Each group then worked in the same classroom every school day for 6–8 weeks. Their performance was significantly better in the classroom that was always cool, on average by 5.7%. However, the subjects knew they were taking part in an experiment, so the observed difference in performance could have been due to a gradual process of discouragement and growing resentment between two groups of pupils and the difference in performance between the groups did indeed increase over time. Just prior to this demonstration, a comprehensive set of behavioural experiments on the effects of classroom temperatures on the performance of schoolwork was carried out in Sweden by one of us [20]. In these experiments, three parallel classes of 9–10-year-old children were exposed for two hours to each of three classroom temperatures: 20, 27 and 30 °C, encountered in balanced order, and four classes of 11–12-year-old children were similarly exposed to 20 and 30 °C [21]. The children's performance of both types of task was significantly lower at 27 and 30 °C in comparison with 20 °C. The magnitude of the negative effect of temperature on performance was for some tasks as great as 30%. In these experiments the appearance and behaviour of the children were systematically observed from behind one-way glass [22]: at the higher temperatures, girls were significantly more restless although they continued to work, while boys behaved significantly more often in undisciplined ways that interrupted their work. In a related experiment in a language laboratory, significant and negative effects of artificially raising the temperature from 20 °C to 27 °C could be shown when the children had to listen and then speak [23]. In a further experiment in this series, carried out in a climate chamber in England, groups of four 12-year-old boys were exposed to 20, 23.5 and 27 °C in balanced order [24]: children performed schoolwork significantly more slowly at the highest temperature.

The present paper summarizes the results of a major series of field intervention experiments by the present authors, completed in 2006. These experiments examined the effects of poor indoor environmental quality (temperature and air quality) on the performance of schoolwork by children. In studies of adults in an office situation it has been found that thermal discomfort distracts attention and generates complaints, that warmth lowers arousal, exacerbates Sick Building Syndrome (SBS) symptoms and has a negative effect on mental work, and that the performance of office work is negatively affected by poor indoor air quality [25,26]. The experiments described below were undertaken to discover whether children in classrooms are similarly affected by warmth and by poor air quality.

2. Experiments on the effects of classroom air quality and temperature on the performance of schoolwork by children

Seven independent field intervention experiments were carried out in elementary schools that were already mechanically ventilated with 100% outdoor air, to determine whether: (1) Avoiding elevated temperatures in classrooms during warm weather; (2) Improving classroom air quality by increasing classroom ventilation; and (3) Reducing the concentration of airborne particles, could improve the performance of schoolwork by children, and if so, by how much. These interventions were carried out in pairs of classrooms in five different schools. Balanced supply and exhaust ventilation was already installed and in operation in all of the classrooms. A total of 380 children aged from 10 to 12 years old took part, in classes numbering from 17 to 24 children.

2.1. Experimental approach

In three experiments carried out in late summer and in winter, the existing outdoor air supply rate per person was increased from about 3 to about 10 L/s by altering the mechanical ventilation system [25,26]: the fan capacity was increased and the system was rebalanced to direct more outdoor air to first one of the two classrooms in which performance was being compared, then the other. The actual effective ventilation rates in the classrooms were estimated with a general mass balance equation [27] from continuous measurements of CO_2 made when pupils were in the classrooms, using teachers' records of the number of pupils present. In the first of the three experiments in which outdoor air supply rate was modified, the mean effective ventilation rate was about 4 L/s per person and 8.5 L/s per person at the two outdoor air supply rates. In the second experiment the corresponding values were 3.0 L/s per person and 6.5 L/s per person, while in the third experiment they were 5 L/s per person and 9.5 L/s person. Average CO_2 levels measured in the occupied classrooms under the two