THE EFFECTS OF CLASSROOM AIR TEMPERATURE AND OUTDOOR AIR SUPPLY RATE ON THE PERFORMANCE OF SCHOOL WORK BY CHILDREN

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ABSTRACT
A field intervention experiment was conducted in two classes of 10-year-old children. Average air temperatures were reduced from 23.6°C to 20°C and outdoor air supply rates were increased from 5.2 to 9.6 L/s per person in a 2x2 crossover design, each condition lasting a week. Tasks representing 8 different aspects of school work, from reading to mathematics, were performed during appropriate lessons and the children marked visual-analogue scales each week to indicate SBS symptom intensity. Increased ventilation rate increased work rate in addition, multiplication and number checking ($P<0.05$), and subtraction ($P<0.06$). Reduced temperature increased work rate in subtraction and reading ($P<0.001$), and reduced errors when checking a transcript against a recorded voice reading aloud ($P<0.07$). Reduced temperature at increased ventilation rate increased work rate in a test of logical thinking ($P<0.03$). This experiment indicates that improving classroom conditions can substantially improve the performance of schoolwork by children.

INDEX TERMS
Performance; Schools; Children; Outdoor air supply rate; Temperature

INTRODUCTION
It is well-documented that indoor environmental quality (IEQ) in schools is both inadequate and 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 the complaints were registered (Angell and Daisey, 1997). The underlying reason is almost always inadequate funding. School facilities are improperly operated and maintained because installation and running budgets have been reduced. As a result outdoor air supply rates per person in classrooms are often so low that carbon dioxide (CO_2) levels are well above the recommended level of 800-1000 ppm (Sowa, 2002), causing poor air quality. There is often no adequate temperature control in classrooms, which especially in warm seasons results in increased temperatures. In spite of the above reports very little is known on how poor IEQ affects schoolwork (Mendell and Heath, 2005), even though performance of schoolwork can have lifelong consequences for a student and society. Most of the available information stems from experiments in 60s and 70s on how classroom temperatures affect school performance (Wyon, 1970; Wyon et al, 1979).

Poor IEQ in office buildings due to increased temperatures and poor air quality s a result of low outdoor air supply rates or poor HVAC maintenance can lead to the reduced performance of office work by adults (Wyon and Wargocki, 2005a,b). It is thus reasonable to suspect that they can also negatively affect school performance by children. Increased temperatures and low outdoor air supply rates can also cause general Sick Building Syndrome (SBS) symptoms such as headache, difficulty in concentrating, fatigue and lethargy (Krogstad et al., 1991; Wargocki et al., 2002) which may have a direct impact on learning. Poor IEQ can affect certain aspects of classroom behaviour that are important for maintaining discipline (Wyon and Holmberg, 1972), and may thus affect learning.

The objective of the present study was to determine whether classroom temperature and outside air supply rate affect schoolwork, to extend knowledge of the effects of poor IEQ on performance from adults in offices to children at school.

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RESEARCH METHODS

The effect of reduced classroom temperature and increased outside air supply rate on the performance of schoolwork was studied in two parallel and identical classes of 10-year-old children (4th grade), in an elementary school providing education for children in the age range from 6 years old to 16 years old. The school is situated in a wealthy community in Northern Zealand, Denmark, and its main building was erected in 1950. The classrooms in which the experiments were carried out were built in 1963. The school buildings are of brick and smoking is not allowed. The classrooms selected for experiments were designed for 28 pupils and have a floor area of 65 m^2 and a volume of 189 m^3. They have typical school furniture and floors covered with linoleum; hooks for overcoats are placed outside the classrooms in the adjacent corridor. The classrooms have south-facing façades that are almost entirely glazed, so that large solar heat gains considerably increase classroom temperatures. Both classrooms are ventilated on weekdays from 7:00 to 16:00 with 100% outdoor air supplied by a mechanical ventilation system that is served by the same air handling unit (AHU), which has pre-heating with a set-point of 20°C and a counter-current heat exchanger but no cooling or humidification. EU7 bag filters are installed in the supply airflow and EU5 in the return. They are changed every 6 months. No other classrooms are served by this AHU. The nominal flow per class is 600 m^3/h to meet the Danish Building Code (BR, 1995) requiring 5 L/s per child, but the actual flow measured prior to the study was 180 m^3/h per class, corresponding to only 1.8 L/s per child. This was probably due to energy reducing measures that had been implemented in the school and to small defects in the AHU. The air is provided to each class through 4 grills placed uniformly on the south façade about 2.5 m above the floor, and it is exhausted through 3 grills close to the floor, in the corridor wall. The ventilation system was installed in the classrooms in 1996 and uses existing bricked shafts to transport the air from the basement, where the AHU is situated, to the classrooms. Its operation is controlled by the computer.

To increase the rate at which outdoor air was supplied to classrooms, the existing electrical motors of the fans in the AHU were replaced with bigger ones and connected to an automated system controlling the ventilation system by a frequency controller, new dampers were installed including butterfly dampers (to perform the airflow measurements), and the grills in the classroom were replaced with bigger ones to increase their effective area. These changes made it possible to increase the airflow to 800 m^3/h per class without a noticeable change in the noise level in the classrooms. To reduce the classroom temperature, wall-mounted split-unit air conditioning was installed in each classroom, consisting of an outdoor unit, situated on the roof, connected to two low-noise indoor units installed on the walls perpendicular to the south façade, above the height of the ventilation inlet grills. Two indoor units were installed to keep the noise level as low as possible. The capacity of the cooling system was sufficient to keep classroom temperature at 20°C with outdoor temperatures up to 30°C.

The experiments were carried out in 4 weeks at the end of August and the beginning of September, 2004. The classroom temperature was reduced from 23-28oC, which would normally occur indoors in this period, down to 20oC and the outside air supply rate was increased from 180 m3/h to 800 m3/h per class in a blind 2x2 crossover design. Each condition was maintained in each classroom for a full week; the new condition was set on Fridays after the last class was over. Prior to the beginning of experiments and after the first 2 weeks of experiments, new supply air filters were installed in the AHU. The fans of the indoor units of the split air-conditioners were operated continuously, independently of whether the cooling was on or off, to create placebo condition. During experiments, the teachers and pupils were allowed to open the windows as usual, and no changes to lesson plan or normal school activities at school were made, so as to maintain the teaching environment and routines as normal as possible.

Each week, in appropriate lessons, the children's usual teachers administered parallel versions of language-based and numerical-based performance tasks representing different aspects of schoolwork, from reading to mathematics. The tasks were selected so that they could be a natural part of an ordinary school day. They included: (1) addition of numbers; (2) multiplication of numbers; (3) subtraction of numbers; (4) checking columns of numbers against each other; (5) sentence comprehension (logical reasoning); (6) proof-reading of text with deliberate errors; (7) acoustic proof-reading of text with deliberate errors when listening to a recorded voice reading it aloud; and (8) reading of text with choice points inserted to determine whether the children understand the text. The tasks were developed to match the difficulty to the age of the children in consultation with the class teachers. They were long enough to ensure that children could not complete them in the time available. Up to 10-15 min was allocated for each test. Four versions of each test were prepared and they were confounded with occasions (i.e. first to fourth week). Performance was measured in terms of speed, i.e. how quickly each pupil worked, and accuracy, i.e. how many errors were committed; in the case of proof-reading, false-positives were also recorded.

Each week the teachers carried out check-list observation of the children's behaviour. Parents and teachers recorded their observations of children's health and mood in logbooks, and the children themselves marked visual-analogue scales each week on the last lesson each Friday to indicate the intensity of various SBS symptoms

and perceptions of environment. CO_2 concentration, temperature, relative humidity and window/door opening behaviour were continuously logged during experiments. Each week spot measurements were made in the classrooms while they were unoccupied of operative temperature, air velocity, airborne particle density and ultrafine particle density, noise, ozone and airflow in the supply air ducts. Weather data for the whole period was registered.

The Statistica software package (version 7) was used for statistical analysis of the data. Shapiro-Wilk's test was used to test whether the data was normally distributed. Repeated measures one-way and 2x2 ANOVA were used for normally distributed data; the least significance difference (LSD) method was used to compare pairs of observations. Friedman two-way analysis of variance was used for not normally distributed data; critical rank was calculated to compare pairs of observations. Wilcoxon matched-pairs signed-ranks test was used to test the effects of main interventions when data was not normally distributed. The P-level was set to 0.05 (2-tail).

The experiment was approved by the Ethics Review Board, Local Authorities and Local School Board.

RESULTS

Table 1 shows the average conditions that were continuously recorded during the period that the classrooms were occupied each day (excluding short breaks between classes) under the four experimental conditions. Spot measurements in empty classrooms showed that the air velocities were <0.11 m/s, turbulence intensity <52% and noise levels 36-38 dB(A); these values did not differ between conditions. Ultrafine particle concentrations in empty classrooms were lower when temperatures were reduced (2100 instead of 3070 counts/cm^3) and at increased outdoor air supply rate (2370 instead of 2800 counts/cm^3). The ratio of indoor-to-outdoor ozone concentration in empty classrooms was about 0.6 at normal (low) outdoor air supply rate and 0.9 at the increased rate; it was not affected by reduced temperature. The average daytime outdoor ozone concentration was 25 ppb during the period of the experiment.

Table 1. *Average conditions continuously logged when classrooms were occupied by children*

Parameter	Temperature			
	Reduced (Low)		Normal (High)	
	Ventilation rate			
	Normal (Low)	Increased (High)	Normal (Low)	Increased (High)
Average number of pupils+teacher (per class)	22+1	23+1	22+1	24+1
Classroom temperature, mean ±sd (^{o}C)	19.2±0.8	20.8±0.9	24.6±1.3	22.5±0.9
Classroom temperature range, min-max (^{o}C)	17.7-21.5	18.5-23.0	20.6-26.7	20.6-25.7
Supply (outdoor) temperature, mean±sd (^{o}C)	16.1±1.4	18.8±1.6	18.6±1.8	16.1±1.5
Classroom RH, mean ±sd (%)	54±4	56±8	52±8	49±8
Supply (outdoor) RH, mean ±sd (%)	69±6	70±12	67±12	69±11
Classroom CO_2, mean±sd (ppm)	1049±154	809±148	952±232	744±176
Supply (outdoor) CO_2, mean±sd (ppm)	398±7	406±15	399±17	396±10
Average classroom peak CO_2 (ppm)	1218	843	1138	831
Total time with 1 or more windows opened (h)	10.7	13.3	26.7	23.5
Total time with main door opened (h)	2.7	6.0*	3.3	2.8
Total time with main door and ≥1 window opened simultaneously (cross-ventilation) (h)	1.6	4.7*	3.1	2.5
Ventilation rate supplied by HVAC (m^3/h)	180	800	180	800
Estimated effective ventilation rate** (m^3/h)	402	800	468	881
(L/s per person)	4.7	9.3	5.7	9.9

* the results from one class; ** supplied by HVAC system plus window ventilation; estimation was made using mass-balance model fitted to the measured changes increase of CO_2 concentration in the occupied class assuming CO_2 production rate per person at 17-18 L/h

Tables 2 and 3 respectively show the effects of reduced classroom temperature and increased outdoor air supply rate on the performance of schoolwork, on perception of the environment and on SBS symptom intensity; only effects that at least approached significance (P<0.10) are presented. The analysis of the observational checklists shows that pupils were more often observed to look around (P<0.03, Wilcoxon), to talk to neighbours (P<0.03, Wilcoxon) and to support their head with their hand (P<0.05, Wilcoxon) when ventilation rate was increased

compared with low (normal) ventilation rate, independently of classroom temperature. There was a tendency for pupil to be more often observed to work hard (P<0.12, Wilcoxon) at increased ventilation rate compared with low (normal) rate, and to cough/sneeze more (P<0.10, Wilcoxon) at high (normal) temperature compared with reduced temperature. Due to too the low return rate it was not possible to analyse parental logbooks.

Table 2. *The effects of interventions and their interactions on performance of schoolwork*

Performance test	Summary of effect
Effects of increased ventilation	
Addition	Increased ventilation rate increased by 14% number of units attempted at a constant error rate* (2x2 ANOVA, P<0.016)
Multiplication	Increased ventilation rate increased by 15% number of units attempted at a constant error rate (2x2 ANOVA, P<0.009)
Number comparison	Increased ventilation rate increased by 14% number of units attempted at a constant error rate (2x2 ANOVA, P<0.05)
Subtraction	Increased ventilation rate tended to increased by 14% number of correctly completed units* (2x2 ANOVA, P<0.06)
Effects of reduced temperature	
Subtraction	Reduced temperature increased number of units attempted by 28% at a constant error rate (2x2 ANOVA, P<0.001)
Acoustic proof-reading	Reduced temperature tended to reduce by 10% number of committed errors (Wilcoxon, P<0.07)
Reading and comprehension	Reduced temperature increased by 24% the pace at which text was read at constant error rate (2x2 ANOVA, P<0.001)
Interaction effects between temperature and ventilation	
Logical reasoning	Interaction between ventilation and temperature (2x2 ANOVA, P<0.04): Reducing temperature at increased ventilation rates increased by 9.5% number of units attempted at a constant error rate (paired t-test, P<0.03)

* the results are only from one class in which a complete 2x2 design was made

Table 3. *The effects of interventions on SBS symptoms and perceptions of environment*

Visual analogue scale	Summary of effect
Effect of increased ventilation	
Too much noise – Completely quiet	Classroom was perceived less quiet at increased ventilation rate (Wilcoxon, P<0.009)
Effect of reduced temperature	
Too cold – Too warm	Classroom was perceived less warm at reduced temperature (Wilcoxon, P<0.0001)
Draughty – Air still	The air was perceived less still at reduced temperature (Wilcoxon, P<0.0001)
Poor air – Fresh Air	The air was perceived more fresh at reduced temperature (Wilcoxon, P<0.03)
Too little light – Too much light	Classroom was perceived less bright at reduced temperature (Wilcoxon, P<0.009)
Very hungry - Full	Pupils indicated to be more hungry at reduced temperature (Wilcoxon, P<0.06)

DISCUSSION

The present results support the anticipated negative effect on learning of poor indoor environment in schools. They were obtained in normal classrooms, during normal lessons using exercises that could be a part of a teaching curriculum that were administered by teachers, without introducing any restrictions to daily routines in the school, e.g. concerning the opening of windows/doors. This high degree of realism during the exposures adds validity to the observed results, taking into account that the performance of as many as 7 out of the 8 tests applied was affected by the interventions, all in the expected direction.

Due to lower than normal outdoor temperatures and opening of windows, the high temperature in the classrooms was lower than expected, especially at the increased outdoor air supply rate. This resulted in a difference of 3.5 K between the average temperatures in each condition (3.9 K in terms of maximum registered temperatures). Direct sunshine will have increased the thermal stress experienced in the warmer condition. Opening of windows raised total outdoor air supply rates above what had been intended. The low outdoor air supply rate corresponded to 5 L/s per person, and met the requirements for pupils in educational facilities in Denmark (BR, 1995). The

high rate was about 10 L/s per person, which is the minimum recommended for adults in office buildings in Europe. It should be emphasized that negative effects on performance were observed even though the children were exposed to the classroom environment for only 2.3 h per day on average, which is much shorter than in earlier experiments on adults performing simulated office work (Wyon and Wargocki, 2005b).

CONCLUSIONS AND IMPLICATIONS

- Reduced temperatures in summer and increased outdoor air supply rates have positive effect on the performance of schoolwork by children.
- The present results were obtained with Danish pupils but can be generalized to other countries in Europe and the USA because the conditions in the selected classrooms and the level of education and educational programs in Denmark are quite similar to those in the other developed countries.

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