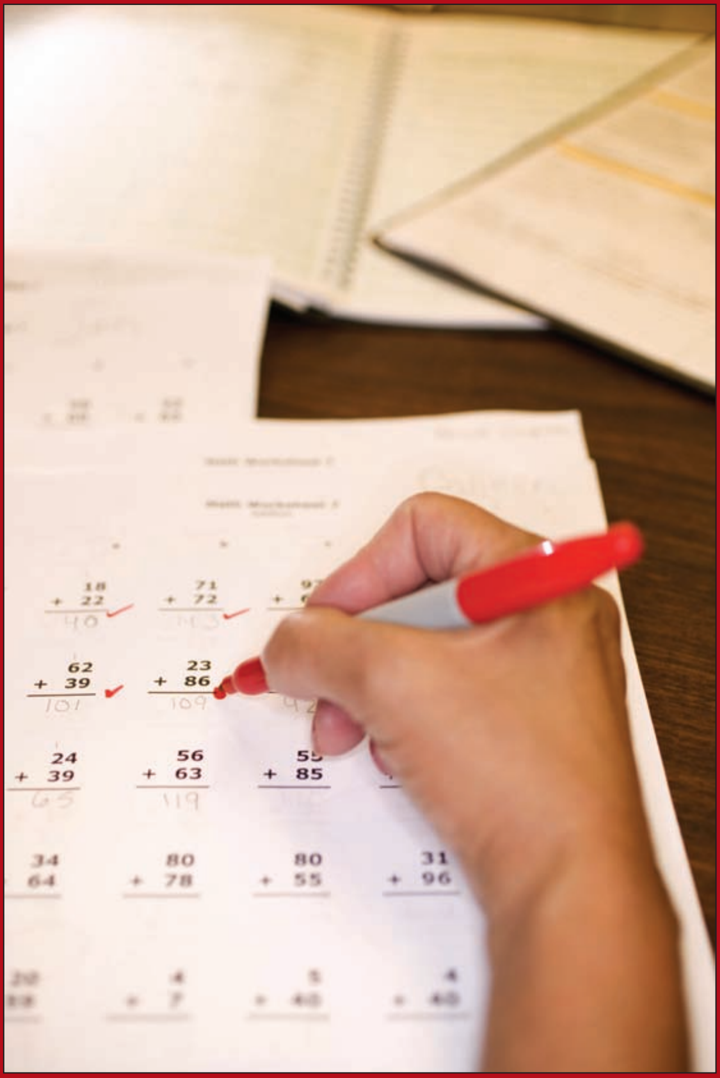
'...air quality and temperatures in classrooms are important factors in the learning process and improving them should be given as much priority as improving teaching materials and methods.'



Research Report on

Effects of HVAC On Student Performance

By **Pawel Wargocki, Ph.D.;** and **David P. Wyon, Ph.D.,** Member ASHRAE

Poor indoor air quality and high indoor air temperatures have been shown to negatively affect adults' performance of office work,[1,2] but little information exists on whether they also have negative effects on the performance of schoolwork by children. This was the conclusion of a recent wide-ranging and authoritative review of published research that is relevant to school classrooms.[3]

The only available data on the effects of classroom temperatures originate from studies performed in the 1960s and 1970s. In one series of scientific experiments,[4] with exposures lasting only two lessons, the performance of tests of reading and mathematics was reduced by as much as 30% at 27°C (81°F) in comparison with 20°C (68°F).

Another study,[5] a comparison over six to eight weeks of test performance in two adjacent classrooms, one with and one without air conditioning, found that performance was about 5.7% better at the lower temperature (classroom air temperatures averaged 22.5°C [72.5°F] and 26°C [78.8°F] respectively). However, this small but increasing difference in test performance could have been due to gradually increasing resentment rather than to any direct effect of temperature, as the children were not used as their own controls.

With regards to the effects of classroom air quality, the only available data originate from a study that found a weak association between increases in carbon dioxide (CO_2) levels in classrooms in a range from 600 to 3,800 ppm and increase in simple reaction time as measured with a diagnostic psychological test, which must be considered a dubious predictor of the performance of schoolwork.[6] Furthermore, this study did not eliminate possibly confounding factors, as different schools were compared.

Another study showed that pollutants emitted from gas heaters in homes negatively affect school attendance.[7] It found an association between attendance and conditions in homes rather than in schools, and simply assumed that attendance is a good predictor of school performance. Although one study showed poor maintenance in schools might be associated with the poor academic achievement of the children attending them,[8] this link may not be causal, that is, it simply may be an example of the negative consequences of the multiple factors that make up an underachieving school collection area.

This lack of knowledge concerning the effects of poor classroom environmental conditions on schoolwork is surprising, considering that environmental conditions in schools have been found to be both inadequate and frequently much worse than in office buildings.[9,10] The most common defects in schools included poor building construction and maintenance; poor cleaning; insufficient outdoor air supplied to occupied spaces; water leaks; inadequate exhaust airflows; poor air distribution or balance; poor maintenance of heating, ventilation and air-conditioning systems; water leaks; and high levels of volatile organic compounds, allergens and molds. Inadequate temperature control in classrooms resulting in elevated temperatures was also common.

The indoor environment in schools has been much less studied than in other buildings such as offices, even though children, unlike adults, are much more vulnerable, must perform work that is not optional and is almost always new to them, and cannot make decisions concerning their school environment. (Children are placed in schools rather than being able to choose one, while adults can change their job, leading to the "healthy worker" effect in surveys of office conditions. Only data from those who can sustain the environmental conditions and, therefore, do not seek other work are ever collected.)

The present study was carried out to fill the present gap in our knowledge of how poor environmental conditions in schools affect the performance of schoolwork. The objective was to investigate whether improving indoor air quality by increasing outdoor air supply rates to classrooms and reducing classroom air temperature during periods with elevated temperatures can improve the performance of schoolwork by children.

About the Authors

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Experimental Approach

Five independent field intervention experiments were carried out in six identical classrooms in an elementary school in Denmark.[11,12] In three experiments carried out in late summer and winter, the outdoor air supply rate per person was increased from about 3 to 9.5 L/s (6.4 to 20.1 cfm), while in two experiments carried out in late summer the temperature was reduced from about 25°C to 20°C (77°F to 68°F). The outdoor air supply rate was increased using the existing mechanical ventilation system while temperature was reduced by either operating or idling split cooling units that had been installed in the classrooms for the purpose of the experiments. The interventions were implemented in a crossover design balanced for order of presentation.

Each experiment was carried out in two parallel classrooms at a time, and each condition lasted for a week. In alternate weeks, the improved condition was imposed in one classroom, the other one acting as the reference condition (unchanged ventilation and temperature) during that week, and the conditions were then switched between the classrooms for the following week (crossover design).

For each condition, tasks representing up to eight different aspects of schoolwork, from reading to mathematics, were performed by 10- to 12-year-old children. The tasks were selected so that they could have been a natural part of an ordinary school day, and were inserted into an appropriate lesson. They included: addition, multiplication and subtraction of numbers; checking columns of numbers against each other; sentence comprehension; proofreading of text with deliberate errors; acoustic proofreading of text with deliberate errors when listening to a recorded voice reading the correct version aloud; and reading of text with choice points inserted to determine whether the children understood the text.

The children's normal class teachers introduced the tasks at fairly even intervals throughout each experimental week, according to the lesson timetable, and each task lasted no more than 10 minutes. No more than one task was performed during one lesson and generally no more than two tasks per day. At the end of each week the pupils reported their perceptions of the environmental conditions in the classrooms and the intensity of any health-related symptoms on questionnaires presented by teachers. Both teachers and pupils were blind to interventions.

During the experiments, the teachers and pupils were allowed to open the windows as usual, and no changes to the lesson plan or normal school activities at school were made to ensure that the teaching environment and daily routines remained as normal as possible. In each condition a sensory panel of adult volunteers assessed the air quality in classrooms after the lessons had ended and children had left the classrooms, so as to avoid any disturbance of school activities.

Experimental Interventions

The classrooms where the experiments were conducted were mechanically ventilated with 100% outdoor air, and to conserve energy, the air-handling units had been adjusted years previously to run below their design capacity. This was one of the reasons that the school was selected for the study because it was possible to modify the existing system to experimentally increase the outdoor air supply rate. This was achieved by fitting a larger fan motor with a frequency controller, and dampers that made it possible to switch the additional airflow achieved between classrooms in alternate weeks. However, no doubt in response to the reduced ventilation rate, teachers had become accustomed to opening windows to improve classroom air quality, and in the interests of realism this was allowed to continue.

Therefore, it was not sufficient to simply measure the mechanically provided airflow rate, as the actual effective ventilation rate was dependent on the frequency and the length of opening of windows, as exemplified in *Figure 1*. The actual effective ventilation rates in the classrooms were estimated from continuous measurements of CO_2 made when pupils were in the classrooms using records of the number of pupils present and assuming that pupils produced CO_2 at a rate similar to adults in offices due to their higher activity, as implied by other studies.[13]

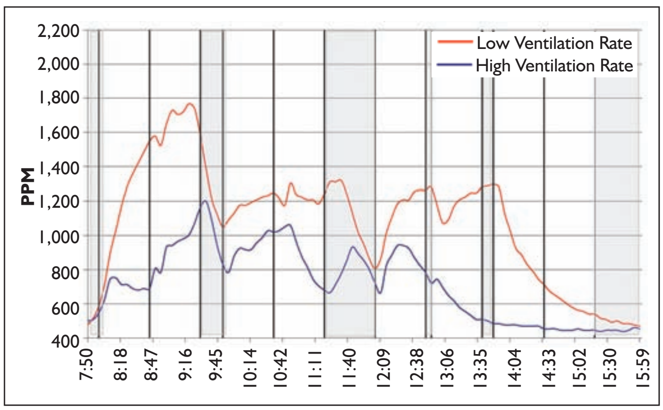

Figure 1: Typical variation of CO_2 in a classroom with normal and increased outdoor air supply rate. Shaded areas indicate periods in which children were absent.

In the first experiment, the effective ventilation rate estimated in this way was about 4 L/s per person (8.5 cfm/person) and 8.5 L/s per person (18 cfm/person) at the two outdoor air supply rates. In the second experiment, the corresponding values were 3 L/s per person (6.4 cfm/person) and 6.5 L/s per person (13.8 cfm/person). In the third experiment, in which classroom temperatures were also manipulated, they were 5 L/s per person (10.6 cfm/person) and 9.5 L/s per person (20.1 cfm/person).

Average CO_2 levels measured in the occupied classrooms under two conditions that were established were 1,280 ppm and 920 ppm in the first experiment, 1,130 ppm and 900 ppm in the second experiment, and 1,000 ppm and 780 ppm in the third experiment. Average momentary peak CO_2 levels under all conditions were in the range from 840 ppm to 1,760 ppm, indicating that these experiments were not comparing worst-case conditions with ideal conditions. These levels are by no means unusual in classrooms everywhere.

In the first experiment, the outdoor air supply rate was manipulated both in weeks in which a used supply air filter was in place, and in weeks in which it had been replaced with a new filter. As no effects of changing the filter on performance could be shown, the data obtained under both filter conditions were pooled. In the other two experiments, new supply air filters were installed each week. Noise levels in classrooms were unaffected by increasing the outdoor air supply rate.

Classroom temperatures were manipulated in two experiments, both in late summer. In the control condition, with no cooling, temperatures rose during the morning and remained high in the afternoon. In the experimental condition, the split cooling units were controlled to maintain a constant temperature, as exemplified in *Figure 2*. Teachers always were allowed to open windows as usual, which they tended to do slightly more often when it was warm in the classroom, this and variations in outdoor temperature made it impossible to replicate conditions exactly in each experiment.

In the first experiment, in which the outdoor air supply rate also was manipulated, the average air temperature in the classrooms was about 20°C (68°F) when cooling was provided and 23.6°C (74.5°F) in the warmer reference condition, so that the difference was 3.6 K (6.5°F). Average maximum temperatures in the two conditions differed by 3.9 K (7.0°F).

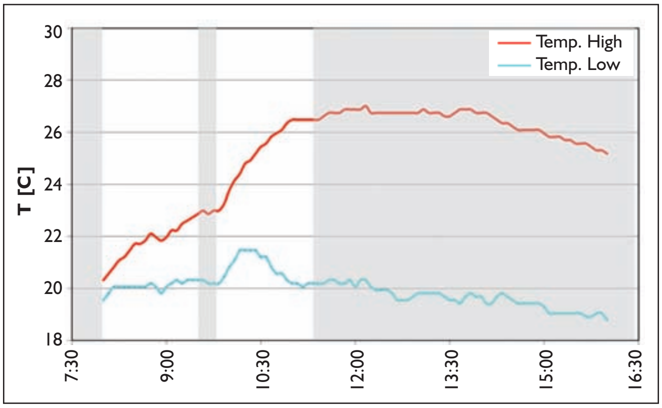

***Figure 2:** Typical air temperature variation in a classroom with and without cooling. Shaded areas indicate when children were absent.*

In the second experiment, which was run in the same two classrooms the following summer, the air temperature in the classrooms was 21.6°C (70.9°F) when cooling was provided and 24.9°C (76.8°F) in the reference condition, i.e., a 3.3 K difference (5.9°F); a slightly lower difference of 2.3 K (4.1°F) was observed between the average maximum temperatures measured. The air circulation fans in the in-classroom cooling units were run continuously, whether or not cooling was being provided, to provide a placebo reference condition and to ensure that the background noise level did not differ systematically between temperature conditions. In these experiments on classroom temperature, new supply air filters were installed each week.

Effects on Children

The detailed results of the experiments have been submitted to ASHRAE's *HVAC&R Research* journal.[11,12] They show that increasing the outdoor air supply rate and reducing moderately elevated classroom temperatures significantly improved the performance of many tasks, mainly in terms of how quickly each pupil worked (speed) but also for some tasks in terms of how many errors were committed (% errors, the percentage of responses that were errors). The improvement was statistically significant at the level of $P \leq 0.05$, meaning that in 100 repetitions the observed result would be obtained by chance no more than five times. The pupils indicated that the classrooms were significantly less warm at reduced temperatures, and that the air was significantly fresher when the outdoor air supply rate was increased or temperature reduced. The children's perception of classroom air quality was supported by the sensory panel assessments of air quality that were made in the same classrooms after the children had gone home. Health-related symptoms (self-reported) generally were unaffected.

When the outdoor air supply rate increased from 3 to 9.5 L/s per person (6.4 to 20.1 cfm/person), the speed at which the children performed four numerical and two language-based tasks improved significantly, and in the case of one numerical task the % errors was significantly reduced.

When the temperature was reduced from 25°C (77°F) to 20°C (68°F), the performance of two arithmetical and two language-based tests improved significantly. The improvement again was in terms of speed, except in the case of an acoustic proofreading exercise where the speed was fixed by the rate of dictation. In this task, reducing the air temperature reduced the percentage of errors missed in one experiment and led to an increase in false-positive identifications in another, indicating that subjects were trying harder.

Using experimental data an attempt was made to establish relationships between the performance of schoolwork and classroom ventilation, and the performance of schoolwork and classroom temperature. The relationships were derived by first normalizing the performance of each individual task, by dividing by average performance throughout each experiment independently of conditions, and then by regressing normalized performance against the outdoor air supply rates and classroom temperatures. The relationships were established independently for the effects on speed and on % errors and using the performance of all tasks presented to pupils. The results are shown in *Figures 3* and *4*. They suggest that doubling outdoor air supply rate would improve the performance of schoolwork in terms of speed by about 8% while reducing classroom air temperature by 1°C (1.8°F) would improve performance in terms of speed by about 2%.

If data only from those tasks in which performance was significantly affected by the interventions were used to establish the relationships, as has been reported elsewhere,[14] doubling outdoor air supply rate would improve the performance of schoolwork in terms of speed by about 14% while reducing classroom air temperature by 1°C (1.8°F) would improve performance in terms of speed by about 4%. Increasing outdoor air supply rate and reducing classroom temperature would not have a measurable effect on the performance of schoolwork in terms of % errors.

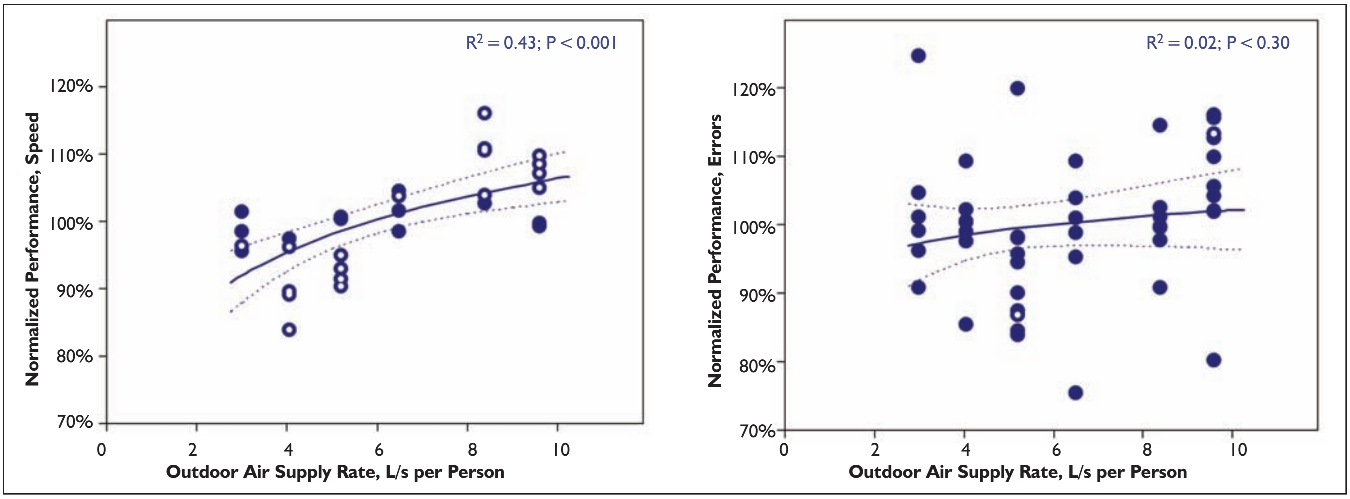

Figure 3: Performance of schoolwork as a function of outdoor air supply rate. Performance is expressed in terms of the speed at which tasks were performed (left) and the percentage of errors committed (right). Dots show performance of individual tasks (open dots indicate those tasks in which performance differed significantly between conditions), while lines show the regression (solid line) with 95% confidence bands (dashed line).

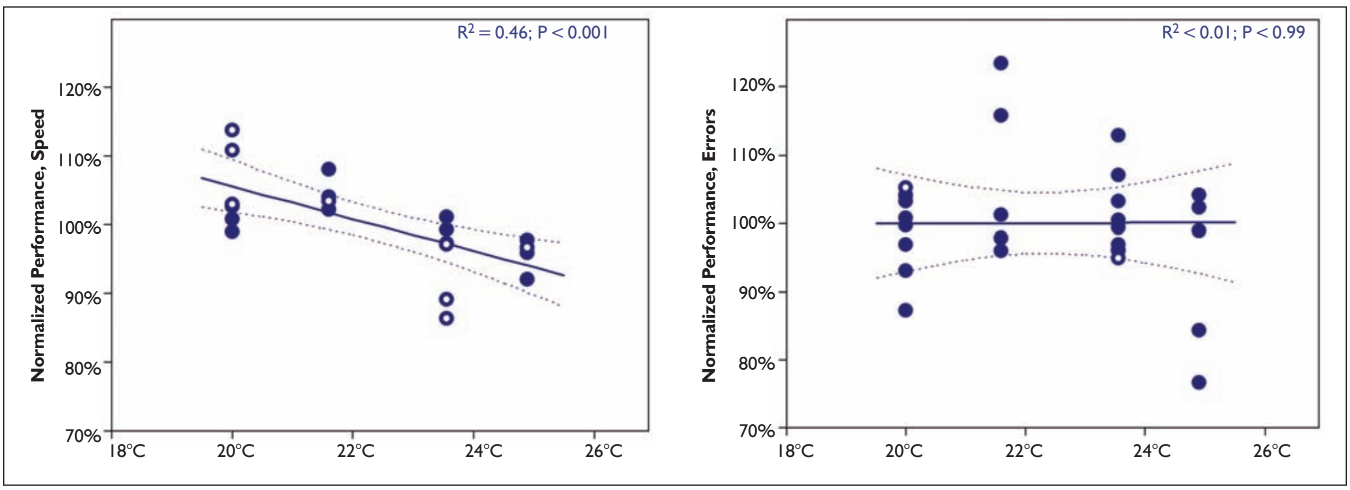

Figure 4: Performance of schoolwork as a function of classroom temperature. Performance is expressed in terms of the speed at which tasks were performed (left) and the percentage of errors committed (right). Dots show performance of individual tasks (open dots indicate those tasks in which performance differed significantly between conditions), while lines show the regression (solid line) with 95% confidence bands (dashed line).

Discussion and Practical Conclusions

The present study was an experimental field study, using children as their own controls, so the observed differences in performance between conditions cannot have been due to differences between groups of children. Both of the conditions to be compared were established at the same time, so external effects such as weather cannot have contributed to the average difference between conditions that was observed. Unlike anecdotal before-after studies of classroom upgrades, this study provides strong evidence that improving indoor air quality in classrooms by increasing the outdoor air supply rate, and reducing moderately elevated classroom temperatures, can substantially improve the performance of a wide range of tasks characteristic of schoolwork, from rule-based logical and mathematical tasks requiring concentration and logical thinking to language-based tasks requiring concentration and comprehension.

The magnitude of the effects on the performance of schoolwork is larger than was found for the performance of office work by adults.[1,2] This suggests that children are more susceptible to environmental conditions, although the observed difference between adults and children may have occurred because adults are expected to overcome the negative effects of indoor environmental conditions to meet deadlines, to complete projects, to follow orders, etc.

Even though the mechanisms by which classroom conditions affect children are poorly understood, and it still remains to quantify how the observed effects on individual tasks would affect overall progress in learning, it is undeniable that enabling children to complete routine exercises more quickly would leave more time for other school activities.

The present results demonstrate that air quality and temperatures in classrooms are important factors in the learning process and improving them should be given as much priority as improving teaching materials and methods. In the absence of any direct evidence that classroom environmental conditions affect schoolwork, the tendency has been to discount their importance, so that today they are often much worse than in the offices where adults work.[9,10]

Although in the present experiments air quality and temperature were improved by increasing ventilation and cooling, it should be remembered that they can also be improved by many different means, e.g., by eliminating pollution sources, by air cleaning and/or by improving the architectural design, and that the benefits for schoolwork are likely to be the same as were observed in the present experiments.

The present results can be generalized to other developed countries, where the climate, classroom conditions, level of education and educational approach often are similar to those in Denmark. It seems likely that the observed positive impact on the performance of schoolwork that can be achieved by preventing children from feeling too warm also would occur in warmer climates. However, this assumption will have to be validated by repeating the study in hotter and more humid climates.

Acknowledgments

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Readers should be aware that the final report has not been submitted to the sponsoring ASHRAE technical committee. Also, subsequent articles in *HVAC&R Research* could differ in some ways, including the conclusions and analysis.

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