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Indoor Environmental Quality in Schools and Academic Performance of Students: Studies from 2004 to Present

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ABSTRACT

A pilot study investigating classroom ventilation rates, and their association with student performance was conducted within a school district in the USA in the spring term 2004. Data on classroom CO_2 concentrations were recorded in 5th grade classrooms in fifty four elementary schools. In addition, investigators were able to work with the district to obtain standardized test scores (math and reading), and background data related to the students in the specific classroom studied in each school. Results of the pilot study have been presented by Shaughnessy et al. 2006, demonstrating a modest association between class room ventilation rates and student performance in math standardized test scores, and also a need for further studies with larger sample size and more comprehensive assessment of indoor air quality (IAQ). Preliminary data is being acquired on a new school district in the USA with 50 elementary schools. The new data focus again on the use of CO_2 concentrations as a surrogate for ventilation rates. CO_2 concentrations were logged over a two day period within typical school day occupancies. Other indicators of the indoor environment related to the investigated classrooms were recorded by checklists incorporating a thorough assessment protocol. Thermal comfort parameters and airborne particle concentrations were also measured for the latest round of schools.

INTRODUCTION

Poor indoor air quality may result in conditions, which contribute to health symptoms that decrease performance while at school. In addition, it has been suggested that poor IAQ may directly reduce a person's ability to perform specific mental tasks requiring concentration, calculation, or memory. The poor IAQ, resulting from numerous interrelated factors, have been validated by a combination of visual observations and objective measurements. It is assumed that poor conditions result in reduced attendance, reduced learning potential, and subsequent poor student performance. However, there is limited data linking poor IAQ in the classrooms directly to student academic performance (AP).

Public demand to improve the educational achievements of children is strong; however, faced with budgetary and subsequent maintenance staff shortages, schools have little incentive or ability to protect the children from resultant poor IAQ. Documentation of adverse effects of physical school environments on AP is critical to motivate protective environmental guidelines in schools as a means to increase student performance (Mendell and Heath 2005).

Ventilation rates in schools have been a focus of many investigations related to poor IAQ. One of the primary building-related problems identified in these investigations has been inadequate ventilation with outdoor air. However, inadequate outdoor air can only be considered as an "indicator", not the causal agent for health symptoms reported in problem schools (Daisey & Angell, 1998). With lack of ventilation, the effect of dilution of contaminants is reduced resulting in elevated concentrations of VOCs, particles, and other indoor pollutants. Conventional studies suggest that air exchange rates play an important role in AP in schools. However, these types of studies are almost universally limited by:

1. Sample size, which is usually too small to reach a definitive conclusion
2. AP being estimated by short (1-2 hour) tests, or mental load tests, which may or may not be a surrogate of AP.

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The range of AP should be best reflected results of standardized state and nation-wide tests.

3. Often, absenteeism is identified as a predictor of student performance; however such a measure is not a direct predictor of AP.

Wargocki, and Wyon (2006) improved IAQ in three mechanically ventilated classrooms by increasing the outdoor air supply rates and by adjusting the temperature to lower levels in two additional classrooms. The effect of these intervention strategies on AP was assessed using numerical or language-based tasks with 10-12 year old students. Performance (speed of tasks) in the five schools improved significantly and dose response relationships were developed. The researchers associate tasks with improved IAQ after intervention. The effects are described clearly and supported with statistical tests; however, to what extent the results from numerical and language based tasks reflect student AP is not clear.

In a preliminary study conducted by Shaughnessy et al. (2006), investigators studied the direct association between outdoor ventilation rates and student performance. Fifth grade classrooms, in 54 elementary schools located in the U.S., were monitored for specific IAQ parameters in the classrooms. In addition to ventilation data and visual observations being recorded, investigators were able to work with the school district to obtain standardized test scores and background data related to the students in the specific classroom studied in each school. It was concluded that the outdoor air ventilation rates in the vast majority of the class rooms were well below minimum established standards for classroom environments. A modest association between student performance (standardized math test scores) and ventilation rates was observed in the classrooms studied. A similar trend was also observed for reading standardized test scores (reduced ventilation rate equated to reduced student performance), however the association between reading test scores and ventilation did not reach the level of statistical significance as for the math score. Finally, it was concluded that the observed association between student performance and ventilation should be further explored in studies with a larger sample size. In addition other indicators of poor IAQ should be included (e.g. moisture, clutter, dust accumulation/content, airborne particles) in the final analysis of contributors that may adversely impact student performance.

This study (reported upon in this paper) is specifically designed for school settings and looks directly into the relationship between student AP and IAQ. The study further focuses on assessing the association between AP of school children and indoor air quality (IAQ) in elementary schools within another school district in the U.S. The primary aim is to study if student AP is significantly (in the statistical sense) related to IAQ in classrooms. The research question seeks to establish whether there is an association between the two variables and determine its strength under classroom conditions.

METHODOLOGY

The schools selected are representative of a consistent cross section of elementary schools, and were investigated for ventilation adequacy and several other IAQ parameters. All elementary schools within the district (50 elementary schools) were included in the study. Specific emphasis was given to the classroom under investigation related to the students in the 5^{th} grade study room. Schools in the district normally had more than one section of 5th grade students (multiple classrooms). The study room was selected (only 1 from each school) randomly, except for the one provision that the HVAC system serving the classroom was restricted to that classroom alone (few exceptions to this were noted in schools investigated).

Although the importance of AP is never questioned, reaching consensus on its measurement is elusive. We are not experts in education research. However, the following five randomly selected states employ standardized tests and methods to assess student AP: Illinois, Iowa, California, Kentucky and Oklahoma. This study utilizes statewide tests to evaluate AP and standard measurements of IAQ. AP is a widely used term that is not defined clearly. At grade and high school levels, the state of Maryland provides the following working definition: AP is the percent of eligible public school students in grades 3 to 8 scoring at the satisfactory or excellent level on curriculum-based assessments in six content areas. The areas are reading, writing, mathematics, science and social studies. AP tests are given on a statewide basis at least once a year to test long term knowledge. AP is the level of knowledge or skill acquired or learned as demonstrated by evidence reflecting the total long-term student academic accomplishment. In this study AP denotes knowledge attained over an academic year as demonstrated in results of statewide-standardized tests in five academic areas. Based on the results of our earlier studies, we focused our study on two academic areas: reading and mathematics.

The AP of 5th graders was used because they can generally be assigned to one classroom and take standardized tests annually. The school level results are public record. For the year of classroom IAQ sampling (already accomplished, Spring 2006) the percent of students scoring satisfactory or above in math and reading tests in each studied classroom will be the primary metric of AP used in the study. Investigators may further scale the performance on a more rigorous grade scale based on actual test scores if initial analysis calls for further breakdown.

The assessment of conditions in schools has entailed the collection of detailed information on environmental and building conditions using checklists and measurement instruments. The visual observation data, based on current conditions and building characteristics included:

- *Observations of potential contributors to poor IAQ* - These included, but were not limited to such observations as: degree of clutter, general cleanliness of environment, inadequate maintenance, animals, sources of

VOCs, and sources of particles, sources of moisture, and cleaning regimen.

- *Building characteristics and moisture damage* - The schools were visually investigated for environmental and building characteristics suspected to have an impact on IAQ and occupant health. These included evaluation of condition and performance of structural assemblies, use of materials, occurrence and characteristics of moisture damage and mold growth.

In addition to the visual observation data, detailed measurements were collected from classrooms accommodating the tested students (5th grade level selected for standardized testing) to assess IAQ in the classrooms. Measurements were taken under closed (ventilation provided primarily by mechanical ventilation system) conditions. All classrooms are served primarily by single room dedicated HVAC systems delivering/recirculating air specifically to each classroom (e.g. classrooms were served by rooftop dedicated units for each classroom, unit ventilators, fan coil units, residential style upright systems. The classroom level measurements included:

- *Ventilation and thermal conditions* - Outdoor air exchange rates were estimated using infrared-based carbon dioxide (CO_2) data logging measurement equipment during occupied hours of the day. A minimum of two occupied classroom days were monitored for characterization. CO_2 readings were taken to provide an assessment of the approximate amount of outside air being delivered to classrooms. CO_2 was utilized as a tracer at end of day when classroom was vacated to further define air exchange within the rooms (recognizing these additional data were during unoccupied hours). CO_2 is not normally considered a contaminant in an indoor air investigation, but does provide a reliable surrogate for ventilation within an occupied space. Data loggers were incorporated to also measure and record real-time data on temperature and humidity levels within the classrooms. This also provided a thermal profile of the individual classrooms during occupied hours. HVAC systems serving the individual classrooms were inspected for general hygiene characteristics, functional components (i.e. damper operation, exhausts, control systems, etc) and filter efficiencies.
- *Measurements of airborne particle mass concentrations* - Several sources can increase particle concentrations in buildings, which can adversely affect IAQ. These include building occupants and their activities, flooring characteristics, HVAC systems, emissions from the building (e.g. building materials and microbial growth), and outdoor air (e.g. traffic, long-range transport of pollutants). Real-time airborne particle counts (converted into mass concentration, $\mu g/m^3$) were recorded (data logged for two occupied hour school days) for PM 2.5 readings within the study classrooms and outdoors for all school locations.

DATA ANALYSIS AND INTERPRETATION

Ventilation rates were assessed using CO_2 measurement data. Concentrations were translated into ventilation rates assuming a source term for CO_2 generation, and assuming CO_2 concentrations had reached steady state (CO_2 ss) in the room. Calculation of a source term related to CO_2 generation is based on several factors such as age, body surface area, mass, and level of physical activity (light activity). These values were utilized in estimating the source term carbon dioxide generation rate based on body weight for the students in the study resulting in a value of .0091 cfm per person. This value was subsequently used in the calculation of ventilation rate per child based on carbon dioxide. The ventilation rates can be sufficiently adjusted based on the typical occupancy in the room throughout the school year.

In general, it is believed that the ventilation rates (as well as many of the other IAQ parameters) are overestimates. For example, although all classrooms are occupied during the test period, in many instances there is some degree of transitory occupancy (i.e. lunch breaks, playground breaks, etc.). Because of these occurrences (in addition to cases where ventilation rates are extremely low, i.e. < 0.5 air changes per hour), steady state (equilibrium) CO_2 concentrations may not be fully realized in many of the classrooms. Under these circumstances, the CO_2 concentrations logged during the measurement period, and assumed as steady state, provide an overestimate of actual ventilation conditions. Therefore, assessment based on the results is on “the safe side”, since the probability of making a type I error, i.e. rejecting the null hypothesis (i.e. IAQ is not related to AP) when it is true, is smaller. The volume of outdoor air determined by direct measurements at the air handler was not utilized due to the variability in type of HVAC systems in the classrooms which precluded direct measurements being achieved in all rooms for this study. In addition, calculation of the ventilation rates based on the analysis of the carbon dioxide mass balance equation, without the simplifying assumptions of steady state or a constant generation rate, has not been utilized in this study due to the variability in occupancy in each classroom. It is recognized that these same limitations impose difficulty in using the steady state approach to estimating the ventilation rates in the classrooms; however the same constraints were present in all classrooms which ultimately result in overestimates of the ventilation rates using the equilibrium approach. The ventilation data utilized for this study are not being used to calculate emission rates, but are being used as a comparative/relative measure of differences in ventilation between classrooms. Since measurements were conducted and analysis the same for all classrooms, the results are appropriate for the purposes of this study. As a final note, carbon dioxide tracer decays recorded at the end of the day in each classroom will be further analyzed at a later date to determine ventilation rates for comparison purposes.

In addition to the assessment of the results with respect to the probability of drawing wrong conclusions due to the study design and measurements used, all the statistical techniques will be used only after careful data considerations. Initially, all ventilation data from the schools shall be scrutinized and studied as to the association to AP. Other recorded information (i.e. thermal data, particulate data, checklist information) shall be input and analyzed in the future as funding allows.

Temperature, humidity, and various other data were collected during the study. These data are being input at this time and will be included in subsequent papers reporting on this project.

Statistical Software to Be Used

It is anticipated that all of the recorded data will ultimately be input into a database and analyzed collectively using SPSS statistical package. GAM modeling will be implemented using R software. In addition SAS statistical package version may be used for GEE analysis.

Interpretation of the Results

Investigators have been able to work with the district to obtain background data related to the students in the specific classroom studied in each school. This information related to students (in the *specific* classroom from each school that was studied) includes male/female ratio, attendance rate, and % free lunch program participants (for indication of family income), % gifted enrollment (for indication of the extent to which each class was selective for gifted students), % mobility rate (for indication of the extent to which the students attending the class remained the same through the school year) and % limited English (for indication of cultural / lingual effects). These variables will be considered as possible confounding factors, and the models will be adjusted for observed confounding effects. For example, confounders for the multiple linear regression models are mainly selected based on a larger than 10% change in the estimate for the independent variable of interest.

PRELIMINARY RESULTS/DISCUSSION

The primary set of classroom data have been collected in the spring of 2006. These environmental data are being scrutinized to distill the basic parameters that exist in the classrooms for subsequent analysis related to student test scores. The student test scores and individual classroom student profiles have recently been delivered to the University from the School District personnel. At this time these data are being input into a database for further study. A preliminary review of these data related to ventilation alone (other parameters including T, RH, particles, observations, etc. are to be input for subsequent analysis as future funding allows) is provided herein. Figure 1 displays the ventilation rate (cfm/person) distribution observed from the 50 classrooms tested.

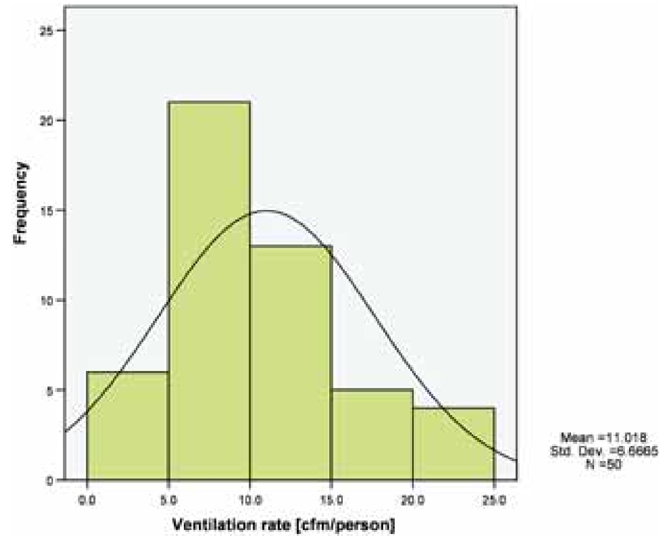

Figure 1 *Ventilation rate distribution.*

At the present state of analysis we present the crude regression coefficients because the study is preliminary and any adjustment and comparison must wait for the complete database. Using math tests score as dependent and ventilation rate as independent variables, univariate linear regression analysis resulted in a crude regression coefficient of 0.382 ($p = 0.315$) for the ventilation rate. In the earlier study the corresponding crude regression coefficient observed was 0.613 ($p = 0.433$). Using reading test score as dependent and ventilation rate as independent variables, univariate linear regression analysis resulted in a regression coefficient of 0.442 ($p = 0.301$) for the ventilation rate. In the earlier study the corresponding crude regression coefficient observed was 0.917 ($p = 0.559$).

Using the same cut off points as with the earlier data; mean math and reading scores for each category are shown in Table 1. The trend is similar to what was reported by Shaughnessy et al. 2006, although the baseline levels for both AP and ventilation rate are higher in the new data set.

In conclusion, a similar trend (increasing ventilation results along with increased test scores) was observed, but further analyses are needed in order to adjust for the confounding factors (in the earlier study, the effect of confounding factors was significant) and non-linear effects. After the new data have been analyzed, it will be further explored whether the statistical power of the analyses can be increased by combining the earlier data (50 schools) with the new data.

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Table 1. Mean Reading and Math Scores for Four Categories of Ventilation Rate

Ventilation Rate [cfm/person]		Math Score	Reading Score
	Mean	68.64	56.62
Ventilation rate 5	N	8	8
	Std. Deviation	13.61	19.33
	Mean	69.89	63.61
5 < Ventilation rate 7.5	N	12	12
	Std. Deviation	16.43	14.26
	Mean	72.18	59.31
7.5 < Ventilation rate 10	N	9	9
	Std. Deviation	19.02	13.01
	Mean	76.32	72.40
Ventilation rate > 10	N	20	20
	Std. Deviation	17.46	21.57
	Mean	72.73	65.27
Total	N	49	49
	Std. Deviation	16.73	18.83

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REFERENCES

Daisey, J. and Angell, W. (1998), "A Survey and Critical review of the Literature on IAQ,

Ventilation and Health Symptoms in Schools", Technical Report LBNL-41517, Lawrence

Berkeley National Laboratory.

Mendell, M. and Heath, H. (2005), "Do Indoor Pollutants and Thermal Conditions in Schools

Affect Student Performance? A Critical Review of the Literature", Indoor Air, 15(1), pp. 27- 52.

Shaughnessy R, Haverinen-Shaughnessy U, Nevalainen A, and Moschandreas D, "Carbon Dioxide Concentrations in Classrooms and Association with Student Performance: A Preliminary Study". In the Proceedings of the 10th International Conference on IAQ and Climate, Beijing, China (2005).

Shaughnessy, R.J., Haverinen Shaughnessy, U., Nevalainen, A., and Moschandreas, D., (2006), "A Preliminary Study on the Association of Ventilation Rates in Classrooms and Student Performance", Indoor Air, 16 (6), pp 465–468.

Wargocki, P. and Wyon, D. (2006), "Effects of HVAC on Student Performance", ASHRAE Journal, 48, pp. 22-28.