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Associations between Classroom Co_2 Concentrations and Student Attendance

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ASSOCIATIONS BETWEEN CLASSROOM CO_2 CONCENTRATIONS AND STUDENT ATTENDANCE

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ABSTRACT

Student attendance in American public schools is a critical factor in securing limited operational funding. Student and teacher attendance influence academic performance. Limited data exist on indoor air and environmental quality (IEQ) in schools, and how IEQ affects attendance, health, or performance. This study explored the association of student absence with measures of indoor minus outdoor carbon dioxide concentration (dCO_2). Absence and dCO_2 data were collected from 409 traditional and 25 portable classrooms from 14 schools located in six school districts in the states of Washington and Idaho. Study classrooms had individual heating, ventilation, and air conditioning (HVAC) systems, except two classrooms without mechanical ventilation. Classroom attributes, student attendance and school-level ethnicity, gender, and socioeconomic status (SES) were included in multivariate modeling. Forty-five percent of classrooms studied had short-term indoor CO_2 concentrations above 1000 parts-per-million (ppm). A 1000 ppm increase in dCO_2 was associated ($p < 0.05$) with a 0.5% to 0.9% decrease in annual average daily attendance (ADA), corresponding to a relative 10% to 20% increase in student absence. Outside air (ventilation) rates estimated from dCO_2 and other collected data were not associated with absence. Annual ADA was 2% higher ($p < 0.0001$) in traditional than in portable classrooms.

PRACTICAL IMPLICATIONS

This study provides motivation for larger school studies to investigate associations of student attendance, and occupant health and student performance, with longer term indoor minus outdoor carbon dioxide concentrations and more accurately measured ventilation rates. If our findings are confirmed, improving classroom ventilation should be considered a practical means of reducing student absence. Adequate or enhanced ventilation may be achieved, for example, with educational training programs for teachers and facilities staff on ventilation system operation and maintenance. Also, technological interventions such as improved automated control systems could provide continuous ventilation during occupied times, regardless of occupant thermal comfort demands.

KEYWORDS
carbon dioxide, schools, children, ventilation, attendance

INTRODUCTION

Existing information on the relationships between indoor air and environmental quality (IEQ) in classrooms and student absence, health, or academic performance is limited and has been reviewed by Heath and Mendell (2002) and Daisey et al. (2003). There have been a few studies of the associations of student health, and to a lesser extent student absence or learning, with types of ventilation system, ventilation rates, indoor temperature and humidity, concentrations of chemical and microbiological pollutants, and amount of daylight (Pepler, 1968; Green, 1974, 1985; Norback et al., 1990; Ruotsalainen et al., 1995; Myhrvold et al., 1996; Myhrvold and Olsen, 1997; Smedje et al., 1997; Walinder et al., 1997a, 1997b, 1998; Meyer et al., 1999; Ahman et al., 2000; Smedje and Norback, 2000, Kim et al., 2002; Sahlberg et al., 2002; Heschong 2002). Some, but certainly not all, studies have found measured IEQ parameters were associated with health, performance, or absence.

Total ventilation, a combination of unintentional air infiltration through the building envelope, natural ventilation through open doors and windows, and mechanical ventilation, provides a means for reducing indoor concentrations of indoor-generated air pollutants. Ventilation standard 62 developed by ASHRAE (2001) specifies a minimum ventilation rate of 7.5 L s^{-1} (15 ft^3 min^{-1}) per occupant for classrooms. Ceiling- or wall-mounted heating, ventilation and air conditioning (HVAC) systems are often used to mechanically ventilate classrooms, although these HVAC systems may provide less ventilation than intended due to design and installation problems, poor maintenance, and because HVAC systems are often not operated continuously during occupancy.

Since measuring the actual ventilation rate is expensive and potentially problematic, the indoor concentration of carbon dioxide (CO_2) has often been used as a surrogate for the ventilation rate per occupant, including in schools (e.g., Lee and Chang, 1999). Indoor CO_2 concentrations exceed outdoor concentrations due to the metabolic production of CO_2 by building occupants. For example, for adult office workers, assuming a ventilation rate of 7.5 L s^{-1} per person and a typical outdoor CO_2 concentration of 350-400 parts-per-million (ppm), a steady state indoor CO_2 concentration of 1000 ppm has been used as an informal dividing line between "adequate" and "inadequate" ventilation (ASHRAE, 2001). However, a CO_2 concentration is only a rough surrogate for ventilation rate, primarily because the measured concentration is often considerably less than the steady state concentration. Despite the limitations of CO_2 concentrations as a measure of ventilation rate, higher concentrations have been associated with increased frequency of health symptoms and increased absence in studies of office workers (Erdmann et al.. 2002; Milton et. al 2000). Available data have indicated many classrooms with ventilation rates below the code minimum or with CO_2 concentrations above 1000 ppm (e.g., Carrer et. al, 2002; Daisey et al., 2003; Shendell et al., 2003a; Lagus Applied Technologies, 1995; RTI, 2003). Therefore, the extent to which lower ventilation rates affect student health, absence, and performance is of particular interest. In general, school absenteeism can serve as an indicator of the student or teacher's overall health condition, although attendance patterns result from a complex interaction of many factors (Weitzman, 1986; Alberg et al., 2003).

This paper presents the results of a study which expanded the work of Prill et al. (2002), who reported findings from rapid IEQ assessment surveys in public schools, including short-term CO_2 measurements in the indoor air, outdoor air, and HVAC supply air diffuser. The present study's hypothesis explored if higher indoor minus outdoor CO_2 concentrations (dCO_2) are associated with increased student absence.

METHODOLOGY

Recruitment of classrooms

Primary and secondary schools in the states of Washington (WA) and Idaho (ID) were approached in the 2000-01 and 2001-02 school years to participate in the Washington State University (WSU) and the Northwest Air Pollution Authority (NWAPA) "3 Step IEQ Program," a streamlined approach for implementing the U.S. EPA's "Tools for Schools" program (Prill et al., 2002). These schools had attended IEQ workshops conducted by WSU or NWAPA, had contacted WSU or NWAPA for IEQ assistance, or were recommended to WSU and NWAPA by other participant school districts (SDs). To select our sample of schools from this group of K-12 schools (n=224), we used a two-step process. First, we only considered primary schools serving K-5 or K-6 (n=134), excluding special education and day care buildings. Second, due to limited resources and travel logistics, we focused on: 1) schools in cities or SDs with the most primary schools; 2) schools where the majority of classrooms were served by individual HVAC systems (or none if just wall heaters were used); and, 3) schools from which daily attendance data, at the student or classroom level, were available. Individual HVAC systems included wall- and ceiling-mounted unit ventilators or heat pumps for heating and/or air conditioning. We excluded classrooms in buildings where one HVAC system served multiple classrooms and classrooms with unvented space heaters for permanent heating systems. The final study sample, after some schools could not participate because they lacked appropriate attendance data records, and given available resources, consisted of 436 classrooms from 22 schools (14 in WA, 8 in ID) in 6 SD (4 in WA, 2 in ID).

IEQ Assessments and CO_2 measurements

The IEQ assessments performed in every classroom consisted of walk-through surveys conducted by a technician together with relevant facilities and administrative staff, and short-term measurements of CO_2 during school hours (Prill et al. 2002). CO_2 measurements were conducted by WSU field technicians using the Q-TRAK Model 8551 instrument (TSI, Inc., Shoreview, MN, USA). Inside each classroom, two short-term (< five-minute average) measurements were conducted sequentially and the measurement times were recorded. First, indoor air CO_2 was assessed near the center of the classroom at the breathing zone height of seated students, but at least one meter from students and not directly underneath the supply air diffusers. Second, the CO_2 concentration in the HVAC supply air was measured using a capture hood to direct undiluted supply air into the instrument sensor. CO_2 instruments were calibrated weekly according to manufacturer specifications using "zero" (N_2, 99.99% pure) and "span" (2010 ppm CO_2, +/- 2%) gases. Instruments were also cross-compared during short-term (< five-minute average) outdoor air CO_2 measurements at each school at locations distant from potential CO_2 sources.

Attendance data

Attendance data were collected from school administrative staff who allowed field technicians access to school attendance records to enter data into a pre-formatted spreadsheet program. For seven schools of one SD, the enrollment and attendance of each individual student on each school day was recorded. For schools in every other SD, we recorded the number of students enrolled, the number absent, and the number in attendance for each classroom and school day. The daily percentages of students in attendance were calculated by pre-coded formulae. Attendance data received a quality control review by LBNL after WSU field technicians sent computer files. This process verified "0" or "blank" (student present) or "1" (student absent) was entered into every cell, vacation periods were left blank, file name room number and grade level designations matched those on the worksheet, and changes in enrollment during the school year were noted with gray-shaded cells. The average daily attendance (number of students attending class divided by number of students enrolled, then converted to a percentage) was calculated for the entire school year and is denoted by "annual ADA" or "yearly attendance." In addition, the same parameter was calculated for the portion of the school year prior to the IEQ inspection and is denoted "pre-visit ADA" or "pre-visit attendance." Although the pre-visit ADA was based on less data than the annual ADA, it was also not affected by any post-inspection ventilation rate changes motivated by recommendations of the inspectors. Annual average absence was calculated as unity minus annual ADA.

Demographic and socioeconomic variables

Aggregate data were collected on demographic and socio-economic variables that could influence student absence and, thus, confound the study findings. These data were obtained for the 2001-02 school year or based on the 2000 national census data available from several public electronic resources[1]. Ferris et al. (1988) reported data on gender and

[1] ID Department of Education (http://www.sde.state.id.us); WA Office of the Superintendent for Public Instruction (http://www.k12.wa.us/edprofile, http://www.k12.wa.us/ → OSPI Programs → child nutrition, data administration, demographics, statistics); National Center for Educational Statistics (http://nces.ed.gov/ccd/schoolsearch).

age (grades) helped explain observed variance in absenteeism. Haines et al. (2002) found the percentage of students in a grade level eligible for subsidized (free) meals at school was related to the average socio-economic status (SES) of the school enrollment in that grade. We collected data, at the school level, on gender and ethnicity (five categories). We also collected school-level data on percent participation in subsidized free lunch programs, reduced-cost lunch programs, and the composite of the free and reduced-cost lunch programs; the composite was used as an indicator of student SES.

CO_2 metric

Based on the measured CO_2 data, we computed the difference between the measured indoor and outdoor CO_2 concentrations (dCO_2). Previous research on CO_2 in school classrooms (Fox et al., 2003) demonstrated a single monitoring location was appropriate for characterizing such indoor contaminant levels when HVAC systems were on, i.e., air was well-mixed. The dCO_2 is only a rough surrogate for ventilation rate because it is based on one-time short-term measurements made at a wide range of times throughout the school day. The major advantage of dCO_2, relative to the ventilation rate estimate described below, is dCO_2 does not rely on any other assumptions.

Estimated ventilation rate

We also used the measured CO_2 data and the measurement time to estimate the total ventilation rate (Q), i.e, the flow rate of outside air into the classroom on the day of the CO_2 measurement prior to the measurement. This approach, however, required several assumptions to be made. The basic approach was to apply the transient mass balance equation for the indoor CO_2 concentration

$$C(t) = \Big(\big(C(\tau) - ((G / Q) + C_o)\big) * EXP\,((-Q / V) * (t-\tau))\Big) + (G / Q) + C_o \qquad \textbf{(1)}$$

where: t is the time of day; τ is the time at the start of the time period for which equation 1 is applied; C is the indoor CO_2 concentration; G is the classroom indoor CO_2 generation rate; Q is the ventilation rate (i.e., flow rate of outside air into the classroom, assumed steady); C_o is the outdoor CO_2 concentration; and V is the estimated classroom volume. We used equation 1 iteratively to determine which value of Q best predicted the measured indoor CO_2 concentration at the recorded measurement time. For these calculations, equation 1 was used for up to eight of the following sequential time periods, P1- P8: P1 = the 30 minutes before arrival of students; P2 = start of school to start of morning recess; P3 = morning recess; P4 = end of morning recess to start of lunch; P5 = lunch; P6 = end of lunch to start of afternoon recess; P7 = afternoon recess; P8 =end of afternoon recess to end of school. During P1, we assumed the teacher was present alone and, therefore, G equaled the CO_2 generation rate of an average adult office worker, which is 0.31 L min^{-1} (ASHRAE, 2001). During P3, P5, and P7, we assumed no one was in the classroom, thus, G equaled zero. When a school did not schedule morning and/or afternoon recess for certain grades, the calculations for those classrooms were adjusted accordingly. During other periods we assumed one teacher and N students were present in the classroom. The estimated generation rate of CO_2 from each student varied with grade level as discussed below. The number of students, N, was based on the number attending class on the school day, obtained from the attendance records. The calculation for period P1 assumed indoor CO_2 concentrations at the start of P1, following the overnight period without occupancy, equaled the outdoor CO_2 concentration.

Substantial effort was required to estimate the rate of CO_2 generation by the students and the resulting estimate has uncertainty, mainly because primary school children's activity levels vary during school. Based on data from Treuth et al. (1998), the 24-hour average CO_2 generation rate of age 10 children (equal numbers of boys and girls) with normal activities is 0.216 L min^{-1}. The basal CO_2 generation rate of the same children was 0.147 L min^{-1}, where basal refers to awake and inactive after a period of rest and no food intake. During sleep, the age 10 children generated 0.132 L min^{-1} of CO_2. With these data, assuming 10 hours of sleep, we calculated the ratio of CO_2 generation when active to the basal CO_2 generation rate to be 1.88, and 10 year old children generate 0.276 L min^{-1} of CO_2 when they are active (not sleeping, with normal activities). We used this rate of CO_2 generation to estimate a student's rate of CO_2 generation at school. To account for the different ages of students at different grade levels, the CO_2 generation of age 10 children was scaled linearly with basal metabolic rate, which is provided as a function of age by ICRP (1993). The resulting equation for CO_2 generation of school children by student age (grade) was:

$$G_{student} = \big((0.0257)*(\text{grade level} + 6) + 0.743\big)*(0.276), \text{ in L min}^{-1} \quad \textbf{(2)}$$

We must emphasize, however, this equation has not been verified.

There are several sources of error in the estimated ventilation rates. Perhaps most important is the application of the standard classroom schedule for the day of CO_2 measurements. If, for example, the actual schedule deviated from the assumed standard schedule because students did not exit the class for recess, large errors could result. In addition, the calculated CO_2 generation rates of the students have uncertainties and inter- and intra-individual variability, and the classrooms volumes were assumed similar by classroom type at each school. Even without these errors, the yearly-average ventilation rate could differ substantially from the estimated rate on the day of CO_2 measurements.

This would be true even if a tracer gas protocol was implemented during the classroom visits to more accurately measure classroom ventilation rates.

Multivariate Analyses

The data were analyzed with SAS software (Enterprise Guide version 1.3 and SAS system release 8.2, SAS Institute, Cary, NC). Descriptive statistics were calculated and the associations of independent variables with student attendance or absence were determined using multivariate linear regression models (ANOVA, PROC GLM). Models were developed for annual ADA, pre-visit ADA, and annual average absence as dependent variables. Independent variables in the final models were: 1) dCO_2, ventilation rate, or ventilation rate per person, as continuous variables; 2) the composite percentage of students at a school participating in subsidized free and reduced-cost lunch programs as an indicator of student and family SES; 3) grade level; 4) type of classroom – traditional or portable; 5) the state in which the classroom was located; and 6) the percentages of Hispanic and/or White/Caucasian students in the school as indicators of ethnic composition.

Depending on the terms in the model, certain data were excluded because the values of one or more input parameters were missing. First, the two classrooms in WA with no mechanical HVAC system and the five classrooms with students in more than one grade level were excluded. Second, calculated ventilation rates included four classrooms with negative values, and so we excluded these classrooms from analyses where ventilation rate was the primary independent variable.

RESULTS

Descriptive Statistics

The average primary school was about 45 years old and most (94%) classrooms were in the main building, i.e., traditional, not portables. There was a fairly equal distribution of classrooms visited across the seven grades except 6th grade classrooms were visited relatively less often because many primary schools in our study only included K-5th grades. Visits to study classrooms were fairly well distributed throughout the school day, although the least number of visits occurred during unoccupied periods. Overall, about 19 of every 20 classrooms in this study were found with the HVAC system on or cycling automatically between on or off. About nine of every 10 classrooms visited were found with windows to the outside closed. In this study, 45% of visited classrooms had measured short-term indoor CO_2 concentrations above 1000 ppm (59% in ID and 35% in WA). Median estimated ventilation rates expressed in air changes per hour (ACH) were highest in portables in WA (3.8 hr^{-1}) and lowest in portables in ID (0.7 hr^{-1}); however, these medians were based on a small sample of 25 total portable classrooms. In traditional classrooms, median estimated ventilation rates were similar (2.2 hr^{-1}) across states, although the mean ACH was higher in classrooms in ID (3.4 hr^{-1}) than in WA (2.6 hr^{-1}). Across states, grades, and room types, the geometric mean annual absence was 5% (median 4.9%, arithmetic mean 5.2%); the mean and median annual ADA were 95%.

Results of multivariate analyses

The primary results of the multivariate modeling are provided in Table 1. The dCO_2 variable was statistically significantly ($p < 0.05$) associated with both the annual ADA and with the pre-visit ADA. For annual ADA, the parameter estimate indicated a 0.5% absolute decrease in attendance, corresponding to a 10% relative increase in the average 5% absence rate, per 1000 ppm increase in dCO_2. For the pre-visit ADA, the parameter estimate indicated a 0.9% absolute decrease in attendance, corresponding to a relative 20% percent increase in the average 5% absence rate, per 1000 ppm increase in dCO_2. The estimated ventilation rate, Q, was not associated with either absence variable.

The traditional classroom type, relative to a portable classroom, was associated with approximately a 2% increase in attendance, and with a 2.5% decrease in absence. In each case, the associations were statistically significant ($p < 0.01$).

A one percent increase in the SES variable, representing the percentage of students receiving free or reduced cost lunch, was associated ($p < 0.001$) with a 0.03% to 0.04% decrease in attendance, and with a 0.02% increase in absence ($p < 0.001$). A one percent increase in the percent of Hispanic students was associated ($p < 0.02$) with a 0.03% *increase* in attendance, and with 0.05% *decrease* in absence ($p < 0.001$).

In most models, the state variable was not associated with attendance and the corresponding parameter estimate was unstable (results not included in Table 1).

Table 1. Key results of multivariate regression modeling.[1]

Basic Model Characteristics				**CO_2 or vent. rate variable**		**room type variable [2]**		**SES variable[3]**		**ethnicity variable[4]**	
No. of class-rooms	attendance or absence variable	CO_2 or vent. rate variable in model	Model R^2	Parameter estimate	p-value	Para-meter estimate	p-value	Para-meter estimate	p-value	Parameter estimate	p-value
395	Yearly attendance%	dCO_2	0.21	-0.0005	0.02	2.29	<0.001	-0.026	0.0003	0.026	0.001
395	Pre-visit attendance%	dCO_2	0.18	-0.0009	0.001	2.33	<0.001	-0.037	<0.0001	0.029	0.02
392	Yearly absence %	Vent. Flow Rate	0.20	-0.1961	0.67	-2.53	<0.001	0.022	0.0007	-0.046	<0.001
392	Yearly absence %	Vent. Flow per person	0.20	0.0035	0.67	-2.53	<0.001	0.022	0.0009	-0.047	<0.001

[1]Parameter estimates represent percent increase in attendance or absence per ppm CO_2, 1 $m^3 s^{-1}$ ventilation rate; or percent increase in the SES or ethnicity variable, or for a traditional classroom relative to a portable classroom. The P-values for the total model were always < 0.0001.
[2]For traditional/main building classrooms relative to portable/relocatable classrooms.
[3]The variable represented the percentage of students at the school receiving either free or reduced lunches.
[4]Percent Hispanic, in some models percent white/Caucasian was also included and significantly associated with attendance.

DISCUSSION

In this study, 1000 ppm increases in the difference between indoor and outdoor CO_2 concentrations were associated with 10% to 20% relative increases in student absence, and the associations were statistically significant. These findings of this study are generally consistent with those of Milton et al. (2000), who found a 50% reduction in ventilation rates in offices, with corresponding increases in indoor CO_2 concentrations, was associated with a 50% increase in short term absence among the office workers occupying the buildings. One potential explanation for our findings and those of Milton et al. (2000) is lower rates of ventilation, indicated by higher CO_2, caused increased communicable respiratory illnesses, probably by increasing the indoor concentration of airborne infectious particles produced during coughing or sneezing. In a review of the literature, Fisk (2000) summarized three studies reporting a reduction in ventilation rate was associated with increases in confirmed respiratory illness.

Because the CO_2 measurements in this study were short-term, five-minute, measurements made on a single school day at variable times of day, they should be considered only rough surrogates for the long-term average classroom ventilation rates that may affect long-term average absence rates. In general, random[2] errors in an independent variable, in this case the errors from using short-term CO_2 as a measure of long-term average ventilation rate, will tend to obscure and weaken associations with the dependent variable (in this case, attendance or absence). Our estimation of ventilation rates based on the measured CO_2 concentrations, the measurement times, and the standard classroom schedules by school by grade were an attempt to derive a ventilation rate estimate with less error. We expected the ventilation rate estimate to be more strongly associated with student absence; however, associations were not close to being statistically significant. There are two potential interpretations for the discrepancy between the dCO_2 and the ventilation-rate findings. The ventilation rate estimates may have large errors due to the uncertain assumptions mentioned in the methodology section of this paper. Alternatively, the ventilation rate estimates could be more reliable than the dCO_2 data for estimating long term average ventilation rates, suggesting the association of dCO_2 with absence was spurious and due to confounding or systematic bias.

We are not aware of large uncontrolled sources of bias likely to create erroneous associations of higher dCO_2 concentrations with increased absence. The models contain variables controlling for SES, classroom type, grade level, ethnic composition, and the State in which the classrooms are located. Thus, we have controlled for the most obvious sources of confounding bias. However, it is still possible some unknown classroom factor, which increases absence rates, is positively correlated with the measured classroom CO_2 concentrations.

This study confirms previous findings of high CO_2 concentrations in classrooms, which indicated classroom ventilation rates were often below the minimum rates specified in codes. In this study, almost half of the CO_2 concentrations were above 1000 ppm and 4.5% were above 2000 ppm. If the measured CO_2 concentrations had been maximum or steady state values, a substantially larger proportion would be expected to exceed 1000 ppm. Thus, it is likely more than half of the classrooms in this study had ventilation rates less than specified in current minimum ventilation standards.

The substantially higher rate of absence in portable classrooms, relative to traditional classrooms, is notable. We do not have a clear explanation for this finding. It

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[2] Errors that are not correlated with the value of the dependent variable

is not known whether portable classrooms have inferior IEQ relative to traditional classrooms, though recent evidence in Los Angeles County has suggested relatively higher indoor air concentrations of toxic and odorous volatile organic compounds are possible in portable classrooms (Shendell et al., 2003b). In addition, it is not known whether inferior IEQ could cause such a large increase in absence. Although the higher absence rate in portable classrooms was statistically significant, the small sample (25 classrooms) should be considered. Before drawing conclusions, other studies should compare absence rates in portable and traditional classrooms.

Finally, we note how changes in ventilation or in any other factor affecting student attendance will influence the funding provided to many SDs, because funding is linked to annual ADA. For example, in California the most currently available (2001-02) funding rate is $12.08 per student-day not absent (CDE, 2003). For a classroom of 20 children with a 185-day school year (3700 student-days), a 1% decrease in annual ADA (or 20% relative increase in absence) is $450 per classroom in funding lost to the SD.

CONCLUSIONS

The major findings of this study were as follows:

- A 1000 ppm increase in the elevation of the indoor CO_2 concentration above the outdoor concentration was associated ($p < 0.05$) with a 0.5% to 0.9% decrease in yearly attendance, corresponding to a relative 10% to 20% relative increase in student absence.
- An estimated outside air supply (ventilation) rate, based on CO_2 measurements and classroom schedules, was not associated with absence.
- Yearly attendance was 2% higher ($p < 0.0001$) in traditional than in portable classrooms.

- Based on the measured CO_2 concentrations, we estimated ventilation rates in at least 50% of the classrooms were less than 7.5 L s^{-1} per person, which is the minimum rate specified in most codes and standards.

Since this study was based on analyses of previously collected CO_2 data, general conclusions should not be drawn from the observed linkage of higher CO_2 levels with increased absence. This study, however, does provide motivation for larger studies designed specifically to investigate the linkage of longer term CO_2 concentration data and more accurately measured ventilation rates with student absence.

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REFERENCES

Ahman, M, Lundin, A, Musabasic, V, Soderman, E. (2000). Improved Health After Intervention in a School with Moisture Problems. *Indoor Air*, **10**: 57-62.

Alberg, AJ, Diette, GB, Ford, JG. (2003). Invited Comentary: Attendance and Absence as Markers of Health Status—The Example of Active and Passive Cigarette Smoking. *American Journal of Epidemiology*, **157** (10): 870-73.

ASHRAE (2001) *Standard 62, Ventilation for acceptable indoor air quality*. American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc. Atlanta, GA.

California Department of Education (CDE). (2003). "Schedule of Apportionment, Categorical Program per ADA, Fiscal Year 2001-02 (per ADA Rate = $12.08)." http://www.cde.ca.gov/fiscal/categorical/categoricalallocation0102.pdf, accessed July 1, 2003.

Carrer, P, Bruinen de Bruin, Y, Franchi, M, Valovirta, E. (2002). The EFA project: indoor air quality in European schools. In: *Proceedings of Indoor Air 2002*, Vol. 2, pp. 794-799.

Daisey, JM, Angell, WJ, Apte, MG. (2003). Indoor Air Quality, Ventilation and Health Symptoms in Schools: An Analysis of Existing Information. *Indoor Air*, **13** (1): 53-64. (LBNL-48287).

Erdmann, C.A., Steiner, K.C,, Apte, M.G., (2002) "Indoor carbon dioxide concentrations and SBS symptoms in office buildings revisited: Analyses of the 100 building BASE Study dataset". *Proceedings of Indoor Air 2002* Conference, Monterey, CA, Vol. 3, pp. 443-448. Indoor Air 2002, Santa Cruz, CA.

Ferris, GR, Bergin, TG, and Wayne, SJ. (1988). Personal Characteristics, Job Performance, and Absenteeism of Public School Teachers. *Journal of Applied Social Psychology*, **18** (7): 552-63.

Fisk, W.J. (2000) Health and productivity gains from better indoor environments and their relationship with building energy efficiency. *Annual Review of Energy and the Environment* 25(1): 537-566.

Fox, A, Harley, W, Feigley, C, Salzberg, D, Sebastian, A, Larsson, L. (2003). Increased levels of bacterial markers and CO_2 in occupied school rooms. *Journal of Environmental Monitoring*, **5**: 246-52.

Green, GH. (1974). The Effect of Indoor Relative Humidity on Absenteeism and Colds in Schools. *ASHRAE Transactions*, **80** (II): 131-41.

Green, GH. (1985). Indoor Relative Humidities in Winter and the Related Absenteeism. *ASHRAE Transactions*, **91** (1B): 643-53.

Haines, MM, Stansfeld, SA, Head, J, Job, RF. (2002). Multilevel modeling of aircraft noise on performance tests in schools around Heathrow Airport London. Journal of Epidemiology and Community Health, **56** (2): 139-44.

Heath, GA, Mendell, MJ. (2002). Do Indoor Environments in Schools Influence Student Performance? A Review of the Literature. In: *Proceedings of Indoor Air 2002,* Vol. 1, pp. 802-807.

Heschong L (2002) Daylighting and student performance. *ASHRAE Journal* **44**(6): 65-67.

ICRP. (2002). Basic Anatomical and Physiological Data for Use in Radiological Protection: Reference Values (Publication 89). Oxford, U.K.: ICRP and Pergamon Press.

Kim, CS, Lim, YW, Yang, JY, Hong, CS, Shin, DC. (2002). Effect of Indoor CO_2 Concentrations on Wheezing Attacks in Children. *Proceedings of the 9th International Conference on Indoor Air Quality and Climate*, Vol. 2, Monterey, CA, 492-97.

Lagus Applied Technologies, (1995). Air change rates in non-residential buildings in California, Report P400-91-034BCN prepared for the California Energy Commission by Lagus Applied Technologies, San Diego, CA.

Lee, SC and Chang, M. (1999). Indoor air quality investigations at five classrooms. *Indoor Air*, **9** (2): 134-38.

Meyer, HWAL, Nielsen, JB, Hansen, MO, Gravesen, S, Nielsen, PA, Skov, P, Gyntelberg, F. (1999). Building conditions and building-related symptoms in the Copenhagen school study. *Indoor Air*, **2**, 298-99.

Milton DK, Glencross PM, Walters MD. (2000). Risk of sick leave associated with outdoor ventilation level , humidification, and building-related complaints. *Indoor Air* **10** (4): 212-221.

Myhrvold, AN, Olsen, E, Luridsen, Ø. (1996). Indoor Environment in Schools—Pupils Health and Performance in Regard to CO_2 Concentrations. *Proceedings of the 7th International Conference on Indoor Air Quality and Climate*, Vol. 4, Nagoya, Japan, 369-74.

Myhrvold, AN and Olsen, E. (1997). Pupil's Health and Performance Due to Renovation of Schools. *Proceedings of Healthy Buildings/IAQ 1997*, Vol. 1, Washington, D.C., 81-86.

Norbäck, D, Torgen, M, Edling, C. (1990). Volatile organic compounds, respirable dust and personal factors related to prevalence and incidence of sick building syndrome in primary schools. *British Journal of Industrial Medicine*, **47**, 733-741.

Pepler, RDW. (1968). Temperature and learning: An experimental study. *ASHRAE Transactions*, **74**: 211-19.

Prill, R, Blake, D, Hales, D. (2002). School indoor air quality assessment and program implementation. *Proceedings of the 9th International Conference on Indoor Air Quality and Climate*, Vol.3, Monterey, CA, 824-29.

Research Triangle Institute (RTI). (2003). California Portable Classrooms Study, Final Report. RTI International, Research Triangle Park, NC, http://www.arb.ca.gov/research/indoor/pcs/pcs-fr/pcs-fr_v3_pes.pdf, accessed July 2003.

Ruotsalainen, R, Teijonsalo, J, Seppänen, O. (1995). Ventilation and indoor air quality in Finnish schools. In: Flatheim, G, Berg, KR, Edvardsen, K. (eds) *Proceedings of Indoor Air Quality in Practice—moisture and cold climate solutions*, Oslo, Norwegian Society of Chartered Engineers, pp. 489-493.

Sahlberg, B, Smedje, G, Norbäck, D. (2002). Sick building syndrome (SBS) among school employees in the county of Uppsala, Sweden. In: *Proceedings of Indoor Air 2002*, Vol. 3, pp. 494-99.

Shendell, DG, Winer, AM, Weker, RW, Colome, SD. (2003a). Evidence of Inadequate Ventilation in Portable Classrooms: Results of a Pilot Study in Los Angeles County. *Indoor Air*, submitted for publication.

Shendell, DG, Winer, AM, Colome, SD, Stock, TH, Zhang, L, Zhang, J, Maberti, S. (2003b). Air concentrations of VOCs in portable and traditional classrooms: Results of a pilot study in Los Angeles County. *Journal of Exposure Analysis and Environmental Epidemiology*, in press.

Smedje, G, Norbäck, D, Edling, C. (1997). Subjective indoor air quality in schools in relation to exposure. *Indoor Air*, **7** (2), 143-150.

Smedje, G, Norback, D. (2000). New Ventilation Systems at Select Schools in Sweden—Effects on Asthma and Exposure. *Archives of Environmental Health*, **55** (1), 18-25.

Treuth, MS, Adolph, AL, Butte, NF. (1998). Energy Expenditure in Children Predicted from Heart Rate and Activity Calibrated Against Respiration Calorimetry. *American Journal of Physiology—Endocrinology and Metabolism*, **38** (1): E12-E18.

Walinder, R, Norbäck, D, Wieslander, G, Smedje, G, Erwall, C. (1997a). Nasal Congestion in Relation to Low Air Exchange Rate in Schools. *Acta Otolaryngol*, **117**: 724-27.

Walinder, R, Norbäck, D, Wieslander, G, Smedje, G, Erwall, C. (1997b). Nasal Mucosal Swelling in Relation to Low Air Exchange Rates in Schools. *Indoor Air*, **7**: 198-205.

Walinder, R, Norbäck, D, Wieslander, G, Smedje, G, Erwall, C, Venge, P. (1998). Nasal patency and biomarkers in nasal lavage—the significance of air exchange rate and type of ventilation in schools. *International Archives of Occupational and Environmental Health*, **71**: 479-86.

Weitzman, M. (1986). School absence rates as outcome measures in studies of children with chronic illness. *Journal of Chronic Diseases*, **39**: 799-808.