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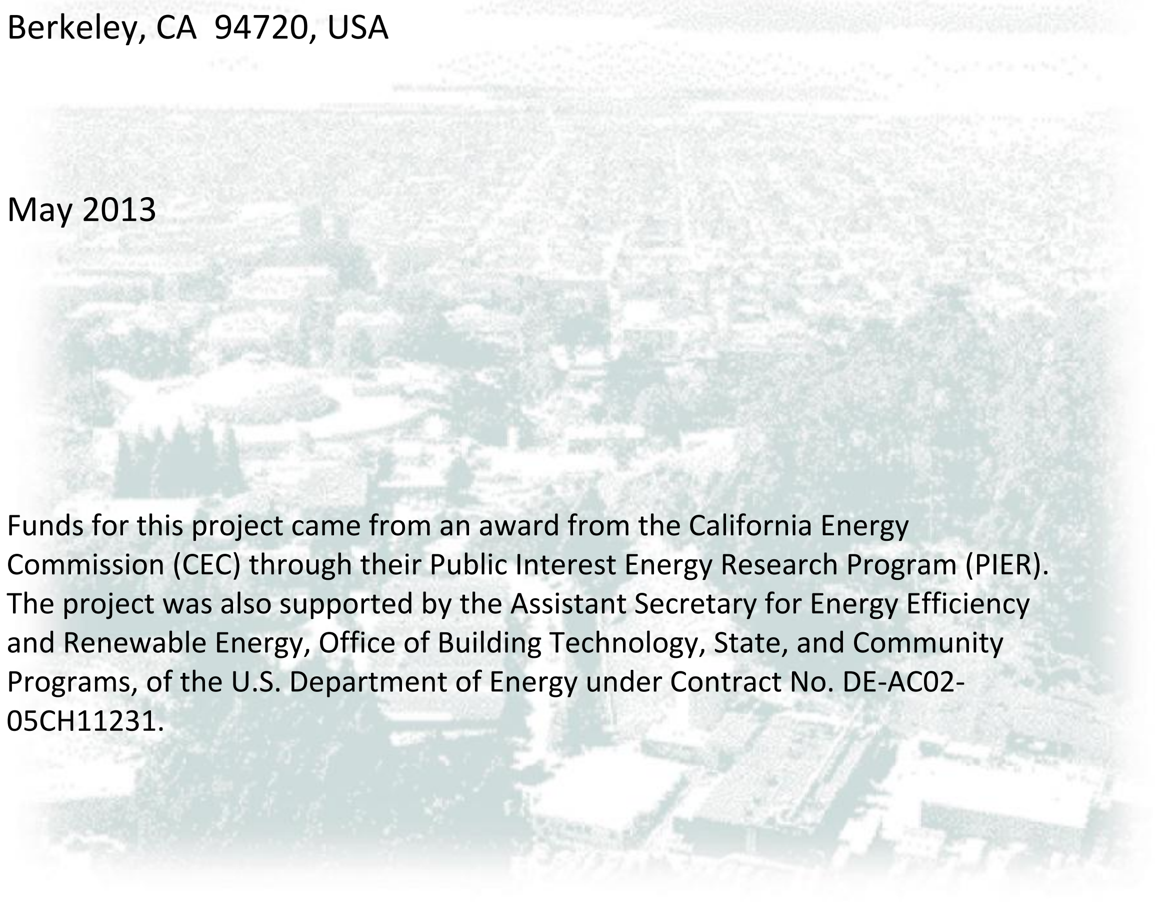

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Abbreviations:

ΔCO_2	indoor minus outdoor CO_2 concentrations
AC	air-conditioning
ADA	Actual Daily Attendance
ASHRAE	American Society for Heating, Refrigerating and Air Conditioning Engineers
BA	Bay Area
CI	confidence interval
CO_2	carbon dioxide
CV	Central Valley
IA	illness absence
K	kindergarten
max	maximum
min	minimum
NB	negative binomial
NHIS	National Health Interview Survey
SC	South Coast
SD	standard deviation
STAR	Standardized Testing and Reporting
VR	ventilation rate
ZI	zero inflated
ZINB	zero-inflated negative binomial

Abstract

Limited evidence associates inadequate classroom ventilation rates (VRs) with increased illness absence (IA). We investigated relationships between VRs and IA in California elementary schools over two school years in 162 3rd-5th grade classrooms in 28 schools in three school districts: South Coast (SC), Bay Area (BA), and Central Valley (CV). We estimated relationships between daily IA and VR (estimated from real-time carbon dioxide) in zero-inflated negative binomial models. We also compared IA benefits and energy costs of increased VRs. All school districts had median VRs below the 7.1 L/sec-person California standard. For each additional 1 L/sec-person of VR, IA was reduced significantly ($p<0.05$) in models for combined districts (-1.6%) and for SC (-1.2%), and non-significantly for districts providing less data: BA (-1.5%) and CV (-1.0%). Assuming associations were causal and generalizable, increasing classroom VRs from the California average (4 L/sec-person) to the State standard would decrease IA by 3.4%, increase attendance-linked funding to schools by $33 million annually, and increase costs only $4 million. Further increasing VRs would provide additional benefits. These findings, while requiring confirmation, suggest that increasing classroom VRs above the State standard would substantially decrease illness absence and produce economic benefits.

Key words:
Carbon dioxide
Indoor environmental quality
Schools
Ventilation
Illness absence

Practical Implications:

These findings suggest a potentially large opportunity to improve the attendance and health of elementary school students in California through provision of increased classroom ventilation. The majority of classrooms in this study provided less ventilation than specified in current State guidelines. If the relationships observed here (and in several prior studies) and the costs and benefits estimated here are confirmed, it would be advantageous to students, their families, and school districts, and highly cost effective, to insure that VRs in elementary school classrooms not only meet but substantially exceed current ventilation guidelines. Because specific exposures and response mechanisms involved have not been determined, it is possible that more energy-efficient alternatives to increased ventilation, such as filtration and reduced indoor emissions, might provide similar benefits.

Background

Ventilation – the supply of outdoor air into a building – decreases indoor concentrations of pollutants generated indoors. Accumulating evidence, mostly from office buildings, suggests that lower ventilation rates (VRs) in buildings are associated with increases in a variety of adverse health effects, such as infectious disease, acute symptoms, and impaired cognition or performance (Li et al., 2007; Seppanen et al., 1999; Sundell et al., 2011). However, this evidence is still limited, especially for schools. School-age children spend more time in school than in any other indoor environment except the home (Klepeis et al., 1996). It is clear that a substantial proportion of current classrooms do not provide even the minimum rates of ventilation specified in standards (Daisey et al., 2003). It is important to determine if classroom VRs influence students' health, as input for future classroom ventilation standards: could minimum allowed VRs be lowered safely to save energy, or should they be kept the same or even raised to protect student health?

Illness absence from schools, which may be related to respiratory infections, asthma, allergies, gastrointestinal infections, or other disease, can serve as an indicator of health effects sufficiently severe to require staying home from school. Limited evidence suggests that lower VRs in offices, schools, and dormitory rooms are associated with increased illness absence (Seppanen, 1999; Sun et al., 2011). Only one available study provides information on classroom VRs and the health of students as indicated by school absences. Shendell et al. (2004) reported that higher classroom ventilation rates were associated with a substantial reduction in student absence. Their study, however, used simple measurements – short, one-time measurements of carbon dioxide (CO_2) in each classroom to estimate VRs throughout a school year, and an outcome of *total* absence, including illness absence but also other types of absence unlikely to be influenced by VR.

The present paper reports findings of a study conducted in California elementary schools on associations between classroom VRs and illness-related school absences, with more detailed data collection. Our primary hypothesis was that decreased VRs in classrooms would be associated with increased illness absences from respiratory infections, due to increased indoor airborne concentrations of respiratory virus. We also compared the estimated costs of increasing classroom VRs to some potential benefits of reduced illness absence.

Methods

To estimate relationships between classroom VRs and illness absence, we collected information from 28 schools in three climate zones within California, over two school years. Web-connected CO_2 sensors in classrooms allowed remote collection of real-time environmental data. Participating school districts provided student absence and demographic data. The collected data allowed estimation of daily ventilation rates and daily illness-related absence by classroom.

We quantified the associations of VRs with absence using statistical models that controlled for several potential confounding factors. We also estimated financial and energy costs for increasing classroom VRs above current levels, and financial benefits from reduced school illness absences: increased revenue to schools from the State for student attendance, and decreased costs to families from lost caregiver wages/time.

Sample Design and Selection

We aggregated the 16 Building Climate Zones of the California Energy Commission (California Energy Commission, 2008) into a smaller number of broader climate regions with similar levels of heating and cooling degree-days (see Fig 1 for boundaries). We included in the study three climate regions with large populations: South Coast (SC), with mild winters and warm summers; Bay Area (BA), with mild summers and winters; and Central Valley (CV), with cold winters and hot summers.

Eligibility criteria for school districts, schools, and classrooms are shown in Data S1, to be found in the on-line supporting information. Within each selected climate region, we invited the largest school district (by student enrollment) to participate. If it was ineligible or declined, we contacted the next largest school district, and continued until arranging participation of an eligible district. Within each participating school district we selected up to 10 elementary schools. To include schools across a range of socioeconomic levels, we ranked schools in each district by the percent of students participating in the free or reduced price meals program (California Department of Education, 2008), used as a surrogate for socioeconomic status, divided the distribution into five quintiles, and selected the two largest schools per quintile, as available. Within each school, we included if possible two each of 3rd, 4th, and 5th grade classrooms.

Student data

The primary outcome variable was daily illness absence count in each classroom. Total daily enrollment per classroom was available from school districts (as the sum of demographic counts per classroom); if less than daily data were available, we backfilled gaps. Other demographic data for students were collected as potential covariates, as classroom-level proportions: participation in free or reduced price meal program, gender, race/ethnicity, English-learner status, gifted status, and special education status.

Environmental data

In each participating classroom and at one outdoor location at each school, we installed a small (2 x 4 x 8 in) web/Ethernet-connected environmental sensor (the “Nose” ™ by PureChoice). The sensors transmitted data to the manufacturer, as 5-minute averaged values of CO_2 concentration (in parts per million, ppm), temperature (in degrees Fahrenheit, ºF), and relative humidity (in %). The nondispersive infrared CO_2 sensors had a resolution of 10 ppm, with accuracy (based on calibration by the manufacturer) of the larger of 5% or 100 ppm within the range 0-2,000 ppm, and typically 5% within the range 2,000-5,000 ppm. The sensors also used a daily auto-calibration process during use to prevent drift and maintain calibration over time (details provided in Data S2). Custom-built protective housings were provided to protect CO2 sensors located outdoors from excessive moisture. Our computer server downloaded data from the PureChoice server daily. If study sensors became inoperable for various periods or permanently during the study, they were restarted or replaced when feasible. Missing sensor data were not estimated. We excluded from VR calculations all so-called “minimum” days in each school (short instruction days of ½ to 2/3 the length of normal school days), as peak indoor CO_2 on these days was less likely to reach true equilibrium levels.

We estimated VR per person (V_o) in L/sec-person in each classroom for each school day during the study, in a mass balance model that used the indoor equilibrium CO_2 concentration minus the outdoor value (Equation 1). To estimate the daily indoor equilibrium CO_2 for each classroom, we used the peak value of a 15-minute moving average of indoor CO_2 values between 7 a.m. - 3 p.m. each day. The corresponding outside CO_2 concentration, originally planned to be the 60-minute outdoor averaged CO_2 for the period ending at the midpoint of the selected 15-minute indoor period, was, due to errors in outdoor readings, estimated in analyses as 400 ppm across all schools.

$$V_o = N/(C_{max15} - C_O) \qquad (1)$$

where
V_o = outdoor air flow rate per person (L/sec-person)
N = CO_2 generation rate per person (see Note)
C_{max15} = maximum 15-minute moving average classroom CO_2 concentration
C_O = outside CO_2 concentration at time of C_{max15} (estimated as 400 ppm)
Note: The occupant CO_2 generation rate (N) is based on a value of 0.0043 L/s for children (Haverinen-Shaughnessy et al., 2011)

We defined several exposure metrics—averaged periods of VR – for analyses to include relevant exposure/disease lag periods for infectious diseases hypothetically causing illness absence in schools. Published information on time lag to disease development after exposure showed a broad range of lag periods for different infectious respiratory agents – one day to three weeks or more (e.g., (Lessler et al., 2009). Little information was available about the relative importance of specific disease agents in school illness absences.

Using daily VR data from the 2-year study, we constructed four aggregate VR metrics: average daily VRs over the 3-, 7-, 14-, and 21-day periods ending immediately prior to each day of modeled illness absence for each school day in each classroom. The 7-day period was considered the primary metric, as it included the 95% upper confidence limits of the incubation period for multiple key respiratory agents – rhinovirus, adenovirus, respiratory syncytial virus, influenza, parainfluenza, and coronavirus (Lessler, 2009). The 3-, 14-, and 21-day metrics were considered exploratory, as no other common viral agents had incubation periods longer than 7 days, and the 3-day metric included upper 95% confidence limits for only rhinovirus, influenza, and parainfluenza (Lessler, 2009).

Other independent variables
Other data variables available for analyses included grade level (3, 4, or 5); total classroom enrollment; building type (permanent or portable); type of ventilation (natural, mechanically ventilated without air-conditioning (AC), or AC); day of week; and winter season (December through February).

Data management and analysis methods

We included data only from eligible periods in each classroom (if single-grade 3rd, 4th, or 5th grade classes, not dedicated special education) (Data S1); only plausible reported illness absence data (some periods in some schools were excluded) (Data S2); and only VR estimates based on plausible CO_2 levels (Data S2). Peak indoor CO_2 levels between 600 ppm and 7,000 ppm were considered plausible for equilibrium levels in occupied classrooms during a school day. Because the CO_2 sensors outdoors turned out to be unstable, with many implausibly high or low values, we excluded all outdoor measurement data and estimated outdoor CO_2 concentrations at 400 ppm, a value from a prior survey that included CO_2 outside of California classrooms (Whitmore et al., 2003).

We performed statistical analyses using STATA (release 11). We first investigated distribution of VRs and illness absence rates. In analytical models at the classroom-day level, we estimated the relative change in absence per each 1 L/sec-person change in VR. The outcome was illness absence count on each classroom day. Including illness absence counts per classroom as the outcome with a covariate of total enrollment per classroom was equivalent to analyzing for proportion of illness absence. Averaged VR period was the primary exposure: one model each for 3-, 7-, 14-, and 21-day exposure periods. We used zero-inflated negative binomial (ZINB) models, because counts of daily illness absence in classrooms were highly skewed, with many 0 values (Yau et al., 2003). ZINB models contain two components: a zero inflation (ZI) model to estimate the probability of each observation to be non-zero, and a negative binomial (NB) model to estimate the values of those observations with a non-zero probability of being positive. We constructed 16 models: for four samples (each of the three school districts and all districts combined), separately for each of the four VR metrics. We estimated the uncertainty (variance) of the estimated coefficients using a bootstrap, re-sampling the schools within districts, in order to reflect the underlying clustered structure of the data. Models were clustered on schools, which were chosen as clusters because classrooms had much more variability within than schools.

Other covariates used in the ZI (logistic regression) component models were day of the week, winter season, and class enrollment. These were selected as potentially related to the possibility of any illness absence in a classroom. In the NB component models, we included additional covariates expected to be related to both VR and IA, or to only IA, but not those related only to VR or those considered in the causal pathway. These same covariates were included in all (separate and combined district) NB component models: day of the week, grade level, class enrollment, proportion in school lunch program, and proportion male. For details regarding inclusion of specific potential covariates, see Data S3 and Figure S1. To avoid the problem of modeling high proportions of zero values for single-day illness absence, we also constructed an alternate set of NB models containing single-day VR values and different multiple-day averages for IA counts: 7-day or 21-day averaged IA.

We made predictions, based on the fitted ZINB models, of illness absence at specific VR levels, in each school district and for all districts combined, with covariates in the model fixed at specific values.

Estimating potential benefits and costs of increased ventilation rates
Methods described in Data S4 were used for estimating, for specific changes in VRs, two kinds of potential benefits associated with reduced illness absence – benefits to school districts, of increased revenue from the State for student attendance, and to families, of decreased costs from lost caregiver wages/time. Calculations and data sources related to increased costs from energy use for specific changes in school VRs are provided in Data S5, Table S1, and Table S2.

Results

We obtained participation of three school districts in California: one each in the SC, BA, and CV climates (see **Figure 1**). We selected subsamples of 10 schools in the SC district and nine in the BA, and included all nine available elementary schools in the CV district. Within each school, we tried to include two classrooms at each of the 3rd, 4th, and 5th grade levels, but the available classroom mix varied slightly from this in some schools. Some participating classrooms, upon changing use and becoming ineligible during the study, were replaced by alternate eligible classrooms when feasible; others were excluded going forward. Only data from eligible periods in each classroom were included in analyses. By the end of the study, we had collected valid data from 162 classrooms in 28 schools. **Table 1** shows the types of buildings and ventilation in the studied classrooms for each school district. The classrooms included 107 in permanent buildings and 55 in portables; 61 with natural ventilation only, 30 with mechanical ventilation without AC, and 71 with AC. While the BA district classrooms included a mixture of the three ventilation types, the SC classrooms included no AC, and the CV schools all had AC. Most classrooms had outdoor air supplied independently, either mechanically or naturally, with air mixing with adjacent rooms only incidentally.

Environmental data
Table 2 provides data on the distributions of peak (as estimates of equilibrium) indoor CO_2 concentrations and estimated VRs in the study classrooms. Ventilation rates differed substantially across districts, with median VRs in the SC, BA, and CV districts of 7.0, 5.1, and 2.6 L/sec-person, respectively. VRs varied most in the SC district, less in the BA, and relatively little in the CV, with ranges between the 5th and 95th percentiles for VR of 18.0, 12.2, and 5.1 L/sec-person, respectively. VRs also varied by building type, with medians in permanent and portable classrooms of 5.2 and 3.1 L/sec-person respectively, and by ventilation type, with medians for natural, mechanical/no AC, and AC of 6.0, 7.6, and 2.8 L/sec-person respectively.

Student data
Table 3 provides descriptive data on the classrooms with valid data available for analyses. All enrolled schools were included except for four in BA, excluded from all analyses because of data-reporting problems (Data S2). Four schools in CV were excluded for one year (Data S2). Average enrollment totaled across all studied classrooms during the study was 2,358. Average student enrollment in each studied classroom was slightly lower in the BA district (25.9) than in the SC (27.3) or CV (26.3). Slightly more males than females were included in each district. Almost three quarters of the students participated in the Free or Reduced Price Meal Program in BA and CV, compared to about half in SC. Proportions of racial/ethnic categories varied across the districts: Asian/Pacific Islander, 7-33%; White, 14-38%; Black, 3-29%, and Latino, 20-51%.

Analyses potentially included over 34,700 classroom days with illness absence data (Table 3). Mean daily classroom proportions of illness absence ranged across districts from 2.11-2.53%, and across grades 3 to 5, were 2.54, 2.25, and 2.30%, respectively. Mean proportion of illness absence was higher in the winter months within each district and overall. More than half of the classroom daily proportions of illness absence, overall or by grade or season, were zero (so the median values of zero are not shown).

Model results

Table S3 provides unadjusted estimates, as incidence rate ratios (IRRs) and 95% confidence intervals (CIs), from ZINB models, for the association between classroom VR metrics and daily classroom proportion of illness absence, for separate district models and the combined district models. Adjusted estimates (Table 4) were very similar to unadjusted estimates. The model assumes a non-linear relationship in which the relative change per VR unit stays constant, but the absolute change decreases as VR increases. The adjusted estimates (coefficients) for VR in the ZINB model indicate: if a classroom were to increase its VR by 1 L/sec-person while holding all other variables in the model constant, the expected proportion of illness absence would be multiplied by a factor equal to the coefficient. Coefficients less than 1.0 indicate decreased illness absence. Changes in illness absence corresponding to multiple-unit increases of VR (in L/sec-person) are estimated by exponentiating the estimates accordingly.

Based on these modeled estimates, for each additional 1 L/sec-person of VR, and considering the four VR summary metrics, illness absence was estimated to be lower (Table 4 and Figure 2): for the SC, BA, and CV districts, by 1.0–1.3%, 1.2–1.5%, and 0.0–2.0%, respectively, and in the model for all districts combined, by 1.4-1.8%. Only estimates in the SC and combined district models had 95% CIs excluding the null. BA and CV had much fewer eligible classroom-day observations (n) in models than SC: 56% and 37% fewer, respectively.

Comparing the range of estimates for each VR metric across the three district models: for each additional 1L/ sec-person of VR, illness absence was estimated to decrease, for the 3-, 7-, 14-, and 21-day periods, by 0.0–1.2%, 1.0–1.5%, 0.9–1.3%, and 1.3–2.0%, respectively. There is a suggestion of increasing associations with longer VR averaging periods, rather than the hypothesized maximum for the 7-day metric (Figure 2).

ZINB models also estimated coefficients for other covariates (not shown). The following results are from the 7-day VR models. For days of the week, the most illness absences were reported in each district on Mondays, followed by Fridays and Tuesdays, with the least on Thursdays and Wednesdays. Proportion in classroom of male gender or with free or reduced price meals was not associated consistently with illness absence overall, with generally nonsignificant associations varying across districts. Exceptions were that illness absence was significantly greater in 3rd than 5th grade in CV but not the other districts, and higher proportion with free or reduced price meals was significantly associated with reduced illness absence in SC but not the other districts.

None of the alternate models (with single-day VRs and multiple-day averaged IAs) converged, so estimates may not be valid (Table S4). Only the 21-day averaged IA models had sufficiently low proportions of zero responses to eliminate the need for a zero inflation model component.

The alternate estimates for VR and IA varied more than those from the primary models. The combined district models, for the 21-day and 7-day averaged IA respectively, estimated 2.4% and 2.2% reductions in IA proportion for each additional 1 L/sec-person, both statistically significant (larger than the estimated reductions from the primary models of 1.8% and 1.6%, respectively.)

Figure 3 plots the predicted counts of illness absence in the three districts and in the combined data, over the observed range of VRs, based on adjusted models using 7-day averaged ventilation rates and specific baseline values of covariates (see figure legend).

Table S5 provides predicted data points corresponding to Figure 3, for 10 example VR levels. Increasing VRs from the current California classroom mean of 4 L/sec-person to 7.1 L/sec-person, the current California Title 24 minimum, would result in 3-5% predicted relative reductions in IA (based on estimates from the three school districts studied). Increasing VRs from current average levels to 9.4 L/sec-person would lead to 7-10% predicted relative reductions in IA; up to 15 L/sec-person, an 11-17% reduction.

Benefits and costs of increased VRs in elementary schools

Estimated losses in ADA revenue to a California school district from the 2.9% illness absence (5.22 annual absence days per student) predicted at the current average classroom VR, using the estimate from the combined districts model, is $153.70 per student or $153,700 per 1,000 students (Data S4). With mean VR increased from 4.0 to 7.1 or to 9.4 L/sec-person, predicted increases in ADA revenue (Table S6) are $5,300 and $10,600, respectively, per 1,000 students. Benefits to families for decreased costs from lost caregiver wages/time, for these two levels of VR increase, amount to approximately $12,800 and $25,600 per 1,000 students, respectively.

If the relationships estimated in this study from three grade levels in three districts were applied to K-12 classrooms throughout California, which requires a number of assumptions, then for the approximately 6,224,000 students (in 303,400 classrooms in 9,900 schools in 2009-10) (California Department of Education, 2012b), an increase in mean VRs from 4 to 7.1 L/sec person would increase annual state funding to school districts, under current formulas, by $33 million (Table 5). Among this population, an increase in VR from 4 to 7.1 L/sec-person would also produce benefits for families, from decreased costs for caregiver time, amounting to $80 million. Valuations of caregiver time include substantial subjectivity and uncertainty. An increase from 4.0 to 9.4 L/sec person would increase annual state funding to school districts by $66 million, and increase benefits to families by $160 million.

The estimated annual (gas and electric) energy costs for increasing the mean VR in California K-12 classrooms from the current level to 7.1 L/s-person or 9.4 L/s-person (Data S6 and Table S7) are $4.0 million or $7.3 million, respectively (Table 5). These estimates have a high expected level of uncertainty. (Note that in California, increasing classroom VRs to this level should be achievable with changes in HVAC operation, without additional costs for increased HVAC equipment capacity; however, this may differ in other geographic areas with more extreme ranges of temperature and relative humidity.)

In comparing these estimated benefits to the estimated costs (Table 5), either of the two specific types of benefits estimated for increased classroom VRs substantially outweighs the estimated energy costs, for VR increase up to 9.4 L/sec-person. Total estimated benefits from VRs increased to 7.1 L/sec-person are $113 million, over 25 times the estimated costs of 4.0 million. Total benefits from an increase to 9.4 L/sec-person, $226 million, are over 30 times the estimated costs of 7.3 million. There are likely to be other financial costs not considered here for increased VRs in classrooms, as well as some potential health costs such as increased intake of pollutants from outdoors. There are also other benefits not considered here, such as reduced costs related to sick leave for teachers and staff, reduced costs of health care for students, and monetized improvements in quality of life for children and families.

Discussion

Over half of the classrooms studied, including over 95% of classrooms in the all-air-conditioned CV district, were supplied with outdoor air at below the CA VR standard of 7.1 L/sec-person. Although observational studies cannot establish causality, the associations found between VR and IA were fairly consistent across school districts, climate zones, and ventilation types. Across the three studied districts, using the 7-day VR metric, IA was reduced 1.0, 1.2, and 1.5% per L/sec-person increase in VR. This was despite substantial differences in both climate (very mild to cold winters and cool to hot summers), types of ventilation (natural to mechanical without AC to AC), and VR levels (medians 2.6-7.0 L/sec-person). The lack of statistical significance for findings in two districts, despite general consistency of the point estimates, seems to be due to limited sample sizes. Future research will be necessary to replicate and validate these findings.

Prior findings

Only one study has investigated absences as indicators of health in offices, across a similar range of VRs as the present study. Milton et al. (2000) found a 2.9% decrease in short-term illness absence in adults per 1 L/sec-person increase in VRs between 12 and 24 L/sec-person. The effect seen in the present study, a 1.0-1.5% reduction in IA per 1 L/sec-person increase in VRs between approximately 2-20 L/sec/person, is less than half as large. Myatt (2002), however, found no difference in illness absence in offices at two very high levels of VR (between 40-45 L/sec-person), as perhaps might be expected.

Classrooms differ from offices and other buildings in the types of indoor pollutant sources, occupant density, and average age of occupants. Only one study has investigated relationships between classroom VRs and the health of students as indicated by absence. Shendell et al. (2004) studied annual average classroom absence rates from 434 traditional and portable classrooms in 22 U.S. schools in Washington and Idaho. Higher classroom VRs were associated with substantially reduced student absence: a decrease of 1,000 ppm in indoor minus outdoor CO_2 concentrations (ΔCO_2) within the range of 10-4,200 ppm was associated with a 10% to 20% relative decrease (0.5-0.9% absolute decrease) in total student absence (which averaged 5.0%). Converting these findings to a comparable metric (Data S7), each additional 1 L/sec-person was associated with a 2.1-7.6% relative decrease in illness absence, approximately 2-5 times larger than the findings here of a 1.0-1.5% relative decrease with this VR change.

Because Shendell et al. (2004) detected such a strong relationship despite the inexact estimates of both VR and plausibly VR-influenced absences (Data S7), the current study, using more accurate ventilation measurement strategies and given the same underlying relationships should have detected stronger associations. Also, we would expect ventilation-related health effects to be larger in schoolchildren than adults, because children are more susceptible to biological and nonbiological pollutants. Yet the current study found much smaller changes in illness absence per unit of VR than Shendell found in schools, and smaller than Milton found for adults in offices, within similar VR ranges. We could hypothesize that Milton, with more precisely defined outcomes of short-term illness absence, had greater power to detect associations, or that our study had fewer errors that could inflate results. Still, we have no clear explanation for our smaller-than-expected findings, and future studies will be needed to shed light on this.

Respiratory infections and illness absence

Over 65% of illness absence in adults may be caused by respiratory infections (Bendrick, 1998; Nichol et al., 1995), but it is not clear how much these infections are influenced by indoor factors. Theory and some empirical evidence (Li, 2007; Milton, 2000; Riley et al., 1978; Riley, 1982; Rudnick and Milton, 2003; Sun, 2011) suggest that lower VRs in buildings could increase airborne transmission of infectious respiratory disease between occupants. VR is not expected to influence exposure to disease agents occurring by direct or indirect contact or by short-range large aerosols such as from nearby sneezing.

Prior studies have reported associations of lower VRs (or higher CO_2 concentrations) with increased respiratory infections, including respiratory infections in dormitories (Sun, 2011) and febrile respiratory illness in barracks (Brundage et al., 1988), as well as with other health effects: building-related symptoms in offices (Erdmann and Apte, 2004; Seppanen, 1999; Wargocki et al., 2002), and respiratory symptoms and nasal patency in school classrooms (Simoni et al., 2011).

We hypothesized that VR rates in classrooms would influence exposures to airborne infectious respiratory agents, and thus affect illness absence among students within 7 days after exposures. We saw instead a suggestion of increasing associations with longer VR-averaging periods: 1.4, 1.6, 1.7, and 1.8% estimated overall reductions for 3-, 7-, 14-, and 21-day averaged VR periods, respectively (Table 4 and Figure 2). This pattern seems less compatible with effects of VR purely on exposure to airborne infectious agents, and more consistent with VR-influenced exposures that have longer-term effects on health or susceptibility. Airborne contaminants produced in classrooms include, in addition to infectious agents and other emissions from occupants, various irritant or toxic chemical emissions: from building materials; building contents such as furniture, carpets, and art supplies; and cleaning and maintenance products. Speculatively, one possible explanation for our findings would be that VR affects indoor airborne irritant exposures on mucous membranes that would influence long-term *susceptibility* to infections (Milton et al., 2000).

Current school VRs

Ventilation rates measured in classrooms often have not met VR standards from the American Society of Heating, Refrigerating and Air-Conditioning (ASHRAE), which are the basis of most building codes. Concentrations of CO_2 in classrooms have often substantially exceeded 1,000 ppm, implying ventilation rates less than 7.4 L/sec-person (Daisey, 2003). Ventilation rates in 45-88% of U.S. public elementary school classrooms were less than specified in codes

(California Air Resources Board, 2004; Corsi et al., 2002; Haverinen-Shaughnessy, 2011; Shaughnessy et al., 2006; Shendell, 2004). Peak CO_2 concentrations exceeded 3,000 in 21% of Texas elementary school classrooms (Corsi, 2002). Errors from measuring peak indoor CO_2 levels below equilibrium cause likely underestimates of this problem. Ventilation in portable classrooms has generally, as in this study, been substantially less than in permanent buildings (California Air Resources Board, 2004; Godwin and Batterman, 2007; Shendell, 2004). Portable classrooms in Idaho had median indoor CO_2 concentrations of 1,590 ppm vs. 670 ppm for permanent classrooms (Shendell, 2004).

Strengths and limitations of study

This is the largest U.S. study reported to date, with the most detailed data on classroom VRs, student illness absence, and demographics. We obtained remote data on daily VRs, IA, and demographic variables from over 160 geographically dispersed classrooms, using web-connected sensors and obtaining student data from school districts in an unidentifiable form not requiring parental permission. This strategy produced a large amount of prospective data at relatively low cost; it also, however, led to limitations in quality of the data. This was especially true in the sensor data on CO_2 concentration and the data from school districts on student illness absence. However, the limitations in these data are likely to have led to reduced power, but not to systematic bias, other than bias toward the null from random measurement errors.

Despite our use of the same sensors in a prior study with no such problems, in this study the communication link to the sensors had a relatively high failure rate (from 25-40% of classroom days, by district), due to problems from software communicating with data networks at schools. This, especially when sensors could not be restarted or replaced, resulted in substantial data loss, compensated for by extension of the study past the original dates. These problems, mostly solved by mid-study, caused loss of power but probably not systematic bias. There were also some implausibly low values in recorded CO_2 levels, presumably due to calibration drift. While the sensors performed daily self-recalibration, this failed to prevent all implausible values, and also prevented post-calibration correction. We excluded implausible indoor CO_2 values from analyses (ranging across districts from 0.3-6.1% of classroom days, essentially all with indoor CO_2 concentrations <600 ppm); any remaining errors from calibration drift would have caused nondifferential misclassification. The CO_2 sensors, not designed or previously used for outdoors due to moisture sensitivity, were installed outdoors in custom built cases for protection against excess moisture. Still, because their data proved unusably erratic (values up to 1,400 ppm, instead of the expected 380-600), we estimated all outdoor CO_2 values at 400 ppm for calculating ΔCO_2 values. If the 400 ppm outdoor estimate used were to have generally underestimated urban outdoor CO_2, this would have led to underestimated VRs and to exaggerated proportions of VRs under current guidelines, but not to changed significance of associations with IA. Random errors in outdoor CO_2 estimations would have biased model estimates toward the null. Additional details on problems with sensor data are provided in Data S2.

Accurate estimation of ventilation rates from CO_2 data is difficult, even assuming accurate real time data on CO_2, which is more than was available in prior studies. Identifying true indoor equilibrium CO_2 levels is challenging in analysis of large amounts of such data. If true equilibrium levels are not reached during a school day, which is very possible in classrooms, measured peak values will underestimate equilibrium levels and overestimate actual VRs. If occupants breathed directly on sensors, peak recorded levels would overestimate true equilibrium concentrations; we reduced likelihood of this by basing VR-estimation on peak 15-minute moving averages in each classroom. Also, although we estimated a fixed VR per day per classroom, ventilation may vary throughout the day in classrooms, as from window openings in naturally ventilated classrooms in warm climates such as SC. Thus, VR estimates in the naturally ventilated SC classrooms may have had more error than those in the air-conditioned CV classrooms; however, because SC had more data, less precision in the estimates of effect was not evident.

Temperatures may have influenced VRs, leading to the possibility that apparent affects of VR were actually caused by temperatures. While 5th percentile and median classroom temperatures were similar across school districts, 95th percentile temperatures in classrooms were high, especially in the non-air-conditioned SC classrooms (Table 1). Higher temperatures would increase VRs in the SC classrooms because of window opening; however, they would reduce VRs in the air-conditioned Central Valley classrooms because of window closing. Despite this opposite effect, relationships between VR and illness absence were similar across these two districts/climate regions. It is also possible that higher temperatures in some classrooms during hot weather, more likely in non-air-conditioned rooms as in the SC district, adversely affected thermal comfort and thus reduced school performance, and in turn increased reported illness absence in these classrooms, compared to air-conditioned classrooms. We do not know of evidence for such an effect.

There is uncertainty about CO_2 generation rates by students. We used a CO_2 emission rate of 0.0043 L/s per student provided by Haverinen-Shaughnessy et al. (2011) based on student age, weight, surface area, and assumed light activity level. If student activity levels were higher, the underestimated CO_2 generation rate would underestimate ventilation rates. If we had assumed students emitted CO_2 at levels equaling adult office workers (0.005 L/s) (ASHRAE, 2010), our calculated ventilation rates would all have been 16% higher. Increased IA would have occurred even at higher levels of VR than predicted here, and the benefits estimated would require higher VRs to achieve.

Some problems in student data were apparent (details in Data S2). One district provided, for each classroom, illness absence data only on days with at least one illness absence, and enrollment numbers only for those days, providing no distinction between classroom days with no illness absences and those with unreported data. Because in one district, several entire schools had implausibly extended periods with no reported illness absences in any classroom (suggesting lack of reporting to the district), and some schools had periods of implausibly large numbers of unverified and unexcused absences at year end (suggesting lack of the required absence verification for extended periods), we excluded illness absence data from these schools for these periods. In another district, we were notified that four schools had inadvertently provided incomplete illness absence data during one school year, so these data were excluded.

Our analysis collected more detailed data on classroom-level demographics and illness absence than the prior study on this topic (Shendell, 2004). Still, our analyses of classroom-level daily illness absence prevalence could not distinguish effects of VR on incident illness from effects on illness duration. Obtaining individual-level linked data on demographics and absence would have allowed a more powerful individual-level analysis of demographically adjusted incident disease. However, this, requiring signed permissions from parents of over 33,000 students in the approximately 160 classrooms, would not have been feasible..

The very high proportions of 0s in data on daily illness absence counts by classroom posed a problem for common statistical analysis models. We used ZINB models, which assume a non-linear relationship in which absolute reduction in illness absence per unit change in VR decreases as VR levels increase, as expected based on our understanding of the hypothesized underlying physical and biologic processes. Alternate models intended to reduce the problem of single-day zero values for illness absence did not converge and produce valid estimates. Other models, however, may better fit the relationship.

The study included 3 types of ventilation in classrooms, distributed very differently within the three participating school districts and building types within each, making it infeasible to investigate potential confounding by this factor.

We did not assess whether differing levels of outdoor air pollutants influenced the effects of VR on student illness absence. In areas with higher ambient pollutants, higher VRs would increase indoor concentrations of these pollutants more, possibly counteracting some benefits of higher VRs from reducing indoor-generated pollutants. Thus these findings may exaggerate benefits in highly polluted locations if outdoor ventilation air is not cleaned of important pollutants.

Because the three school districts included were not selected to be representative of California districts, results from the combined district models may not be generalizable to all California school districts generally. Also, because districts differed in many ways such as in VR ranges, ventilation type, climate, and combinations of some covariates, as well as other ways, analyzing the combined data may produce biased estimates.

Caution should be exercised in extrapolating these findings. For instance, older school children may be less susceptible to ventilation-related pollutants than those studied here, leading to reduced impacts of ventilation on illness absence and related costs. Climates in the studied districts have more moderate temperatures and relative humidities than some other regions of the U.S., and increasing ventilation rates may be more costly in the Midwest or Northeast U.S. due to extreme temperatures, or the southeast U.S. due to extreme relative humidities. Limited data were available in this study on VRs over about 15 L/s-person. In addition, adverse effects of increasing VR in locations with highly polluted outdoor air, or the costs of removing these from incoming ventilation air, must be considered in any decisions about costs and benefits of increased VRs to classrooms.

Implications

The relationships found here are consistent with, but do not prove, a causal relationship between increased VRs in elementary school classrooms and decreased illness absence. Replication, including in additional geographic areas and with schoolchildren of different ages, will be needed to confirm the relationships seen here and in prior studies, and to provide sufficient basis for wider extrapolation as a basis for policy. The relationships here were found not only up to the current recommended VR levels (for an estimated 3-5% reduction in illness absence), but beyond them. For instance, VRs increased to 15 L/sec-person are associated with an estimated 11-17% reduction in illness absence. If the relationships observed here and the estimated costs and benefits are confirmed, it would be advantageous to students, their families, and school districts, and highly cost effective, to insure that VRs in elementary school classrooms substantially exceed current recommended ventilation guidelines. Additional data and analyses would be necessary to refine these estimates of cost and benefit, and to produce estimates for other climates.

Because of the problems with study power seen here despite large amounts of data, future studies should strive for improved data quality. Improved estimation of ventilation rates, through collection of data on classroom dimensions and varying occupancy during the day, in addition to real-time CO_2, in order to use metrics not based on the uncertain achievement of indoor CO_2 equilibrium, would increase study power. Use of instruments of documented reliability and accuracy both indoors and outdoors will also be important. Independent verification of illness absences and collection of detailed data on types of illness absence, although expensive, would increase study power and also improve ability to characterize causal mechanisms.

There are more efficient alternatives to general dilution of indoor pollutants by outside air ventilation for reducing concentrations of indoor contaminants. Improved particle filtration would reduce exposures to some infectious respiratory agents and use less energy than increased ventilation. To the extent that chronic exposures to other indoor contaminants such as chemicals are important in increasing illness absence, reducing indoor emission of these contaminants, or reducing their indoor concentrations with suitable air cleaning systems, may be feasible in lieu of increasing VR.

These findings suggest a potentially large opportunity to improve the attendance and health of elementary school students in California through provision of increased outdoor air ventilation in classrooms. It is thus important that future research attempt to replicate and validate these findings, with more data and including different geographic regions, as a potential basis for policy. This would support classroom ventilation standards that more explicitly reflect health protection as a balance to energy efficiency.

Conclusions

The majority of the studied California elementary school classrooms in this study provided their students with less outdoor air ventilation than specified in current State guidelines. Higher VRs in classrooms were associated consistently with decreased illness absence, although small sample sizes made this association somewhat less certain in some school districts. Keeping VRs below recommended levels in classrooms saves energy and money but, if the associations seen here are causal, has unrecognized but much larger costs from increased health problems and illness absence among students. Increasing VRs *above* the recommended minimum levels, even up to 15 L/sec-person or higher, may further substantially decrease illness absence. It may be advantageous to students, their families, and school districts, and also highly cost effective, for VRs in elementary school classrooms to substantially exceed current recommended ventilation guidelines.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Data S1. Eligibility Criteria for School Districts, Schools, and Classrooms.
Data S2. Details of data collection process and problems, and related changes in study design.
Data S3. Environmental and student covariates.
Data S4. Estimation of selected economic benefits from reduced school illness absence.
Data S5. Calculations and data sources related to increased costs from energy use for specific changes in school VRs.
Data S6. Results: estimated benefits and costs of increased VRs in elementary schools.
Data S7. Considerations for comparison of current findings to findings of Shendell et al. (2004).

Table S1. Current ventilation standards per State of California
Table S2. Current ASHRAE ventilation rate requirements (ASHRAE 2010, p. 12)
Table S3. Unadjusted IRR estimates and 95% confidence intervals (CI) from zero inflated negative binomial models for association between classroom ventilation rate (VR) metrics and daily classroom proportion of illness absence, per increase of 1 L/sec-person VR in observed range of 1-20 L/sec-person.
Table S4. Alternate adjusted IRR estimates and 95% confidence intervals (CI) from zero inflated negative binomial models for association between single-day classroom ventilation rate (VR) and period-averaged daily classroom proportion of illness absence, per increase of 1 L/sec-person VR in observed range of 1-20 L/sec-person (note – none of models producing these estimates converged, so estimates may not be meaningful).
Table S5. Predicted proportion of illness absence at specified outdoor air ventilation rates, based on adjusted models using 7-day averaged ventilation rates, in three California climate zones.
Table S6. Estimated losses in revenue to school districts.
Table S7. Estimates of the energy use and costs for cooling and heating the ventilation air provided to Classrooms in California.

Figure S1. Average annual ventilation rates in naturally ventilation classrooms – an example of why annual average ventilation rates may be a poor proxy for daily exposure in these classrooms

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TABLES

Table 1. Descriptive information on selected study variables

Variables	SC District	BA District	CV District	All Districts
Summer temperature	warm	mild	hot	---
Winter temperature	mild	mild	cold	---
Ranges of monthly mean daily min and max outdoor temperatures in °F (2010)[++]	50-63; 65-74	47-59; 56-78	42-67; 56-99	---
Ranges of monthly mean outdoor relative humidities (2010)[++]	56-77%	64-87%	36-83%	---
Median (5th %, 95th %) of daily average indoor temperatures in °F[+]	75 (69 ,82)	73 (69, 80)	74 (70, 77)	---
Number of schools	10	9	9	28
Number of classrooms	59	52	51	162
Building type for classrooms				
Proportion (number) in permanent buildings	59% (35)	81% (42)	59% (30)	66% (107)
Proportion (number) in portable buildings	41% (24)	19% (10)	41% (21)	34% (55)
Ventilation type for classrooms				
Proportion (number) with natural ventilation	76 % (45)	31% (16)	0% (0)	37% (61)
Proportion (number) with mechanical ventilation, no AC	24% (14)	31% (16)	0% (0)	19% (30)
Proportion (number) with AC	0% (0)	38% (20)	100% (51)	44% (71)
Number of classroom days with ventilation rate data**	11,069	9,615	8,135	28,819
Approximate total enrollment in all 3rd, 4th, and 5th grade classrooms in studied school districts***	30,000	12,000	3,000	45,000

Abbreviations: AC, air-conditioning; BA, Bay Area; CV, Central Valley; max, maximum; min, minimum; SC, South Coast; VR, ventilation rate

+ based on daily average indoor temperatures for studied classrooms in each school district, based on all school days in the included school years during which measured peak CO_2 values fell in the eligible range, but excluding minimum days

++ for same or nearby city in that climate region of California

** includes all those with valid VR data, although may not all be included in models; i.e., it includes all 28 schools and 162 classrooms, even though some classrooms, or entire schools in BA, were excluded from analyses.

*** regardless of whether included in this study; numbers rounded to nearest 1,000; data from California Department of Education (2012a)

SD= http://www1.ncdc.noaa.gov/pub/orders/IPS-C31B3F56-20B5-4D7C-B483-E7DD5445E40E.pdf
Oak=SF-= http://www1.ncdc.noaa.gov/pub/orders/IPS-6AA7120C-D4D0-44D2-923C-A284F1930A49.pdf
T=Fresno= http://www1.ncdc.noaa.gov/pub/orders/IPS-7CAC2CD8-DB7C-40C1-A6D3-E9787417FC72.pdf

Table 2. Distribution of peak (estimated equilibrium) indoor CO_2 concentrations* and estimated ventilation rates by district, building type, and ventilation type

	Peak (estimated equilibrium) CO_2 concentration (ppm)**							VR (L/ sec-person)**						
	5th %ile	25th %ile	50th %ile	75th %ile	95th %ile	Mean	SD	5th %ile	25th %ile	50th %ile	75th %ile	95th %ile	Mean	SD
School District														
SC	654	853	1,140	1,700	2,640	1,350	652	2.31	3.98	7.01	11.40	20.30	8.43	5.53
BA	769	1,040	1,400	2,040	3,220	1,630	770	1.83	3.15	5.14	8.08	14.00	6.17	4.03
CV	1,200	1,850	2,380	3,030	4,170	2,490	901	1.37	1.97	2.61	3.55	6.43	3.11	2.01
Building Type														
Permanent	702	984	1,390	2,000	3,020	1,570	734	1.97	3.23	5.24	8.84	17.10	6.77	4.80
Portable	750	1,260	2,060	2,880	4,080	2,160	1,060	1.40	2.09	3.12	6.03	14.80	4.98	4.53
Ventilation type														
Natural	695	914	1,270	1,813	2,760	1,450	672	2.19	3.66	5.95	10.10	17.50	7.42	4.91
Mechanical / no AC	650	848	1,080	1,420	2,230	1,200	485	2.83	5.05	7.56	11.50	20.60	8.98	5.31
AC	1,010	1,700	2,280	2,950	3,990	2,370	916	1.44	2.03	2.75	3.99	8.50	3.51	2.50

Abbreviations: AC, air-conditioning; BA, Bay Area; CV, Central Valley; SC, South Coast; SD, standard deviation; VR, ventilation rate

* Data in this table include all valid CO_2 measurements, without exclusion due to invalid associated illness absence data.

**Because peak indoor CO_2 concentrations below 600 ppm and above 7,000 ppm were excluded, these constituted the potential minimum and maximum values across all districts for peak (estimated equilibrium) CO_2 concentrations, and the corresponding values for minimum and maximum VRs (0.8 and 25.9 L/sec-person).

Table 3. Demographic and illness absence data, for classrooms and times with student data eligible for analyses*

	SC District	BA District	CV District	All Districts
Number of Schools	10	5	9	24
Number of Classrooms	59	26	51	136
Building type for classrooms				
Proportion (number) in permanent buildings	0.59 (35)	0.88 (23)	0.59 (30)	0.65 (88)
Proportion (number) in portable buildings	0.41 (24)	0.12 (3)	0.41 (21)	0.35 (48)
Ventilation type for classrooms				
Proportion (number) with natural ventilation	0.76 (45)	0.12 (3)	0	0.35 (48)
Proportion (number) with mechanical ventilation, no AC	0.24 (14)	0.38 (10)	0	0.18 (24)
Proportion (number) with AC	0	0.50 (13)	1.0 (51)	0.47 (64)
Average enrollment per classroom (SD)	27.3 (5.6)	25.9 (5.0)	26.3 (4.8)	26.7 (5.3)
Third grade	23	21	21	22
Fourth grade	29	28	29	29
Fifth grade	29	28	30	29
Average combined enrollment of included classrooms	1,401	561	1,089	2,358
Third grade	345	133	301	598
Fourth grade	541	216	393	892
Fifth grade	515	211	394	867
Average proportion male	0.52	0.52	0.52	0.52
Average proportion National School Lunch Program**	0.49	0.76	0.71	0.62
Average proportion Asian or Pacific Islander	0.28	0.33	0.07	0.22
Average proportion White	0.17	0.14	0.38	0.23
Average proportion Black	0.18	0.29	0.03	0.16
Average proportion Latino	0.38	0.20	0.51	0.38
Number of classroom days with illness absence data*	16,807	7,338	10,562	34,707
Mean daily classroom proportion (%) of illness absence (SD)	2.36 (3.2)	2.11 (3.4)	2.53 (3.3)	2.36 (3.3)
3rd grade	2.42	2.48	2.74	2.54
4th grade	2.38	1.61	2.53	2.25
5th grade	2.29	2.32	2.32	2.30
Winter season***	2.84	2.32	2.95	2.75
Non-winter season	2.19	2.02	2.40	2.22

Abbreviations: SD, standard deviation

* based on all valid IA data eligible for inclusion in models, from 136 out of the 162 classrooms described in Table 1; however, some classroom-days included in these data were not included in models if lacking necessary VR data
** official name of the national Free or Reduced Price Lunch Program
*** winter was defined as the months of December, January, and February.

Table 4. Adjusted IRR estimates* and 95% confidence intervals (CI) from zero inflated negative binomial models for association between classroom ventilation rate (VR) metrics and daily classroom proportion of illness absence, per increase of 1 L/sec-person VR in observed range of 1-20 L/sec-person**

	SC District			BA District			CV District			All Districts		
VR averaging period	n	IRR	(95% CI**) p-value	n	IRR	(95% CI**) p-value	n	IRR	(95% CI**) p-value	n	IRR	(95% CI**) p-value
3 days***	13,363	0.990	(0.982-0.998) p=0.01	5,252	0.988	0.963-1.01 p=0.38	9,781	1.000	(0.980-1.02) p=1.0	28,396	0.986	(0.975-0.997) p=0.01
7 days***	14,318	0.988	(0.980-0.997) p=0.01	5,742	0.985	0.951-1.02 p=0.40	10,120	0.990	(0.964-1.02) p=0.47	30,180	0.984	(0.971-0.996) p=0.01
14 days***	14,559	0.987	(0.978-0.997) p=0.008	5,955	0.988	0.945-1.03 p=0.61	10,378	0.991	(0.962-1.02) p=0.54	30,892	0.983	(0.969-0.997)\\ p=0.02
21 days***	14,664	0.987	(0.977-0.997) p=0.01	6,106	0.987	0.940-1.04 p=0.60	10,438	0.980	(0.952-1.01) p=0.19	31,208	0.982	(0.968-0.997) p=0.02

Abbreviations: CI, confidence interval; IRR, incidence rate ratio; L, liter; s, second, VR, ventilation rate;

* estimates are the relative (multiplicative) change in the outcome for each increase of one L/sec-person; models adjusted, in the main part of the model, for grade level, day of the week, proportion free lunch program, and proportion male; and in the zero-inflated part, for day of week, winter season, and total count (from demographics data).

** bootstrapped

*** ending on day prior to day on which illness absence assessed

Table 5. Estimated energy use and costs for cooling and heating the ventilation air provided to K-12 classrooms in California**.

	Energy Use		Costs			Benefits	
	Electricity Use (GWh) {% of total}*	Gas Use (GWh) {% of total}^	Electricity Costs ($)	Gas Costs ($)	Total Increase in Energy Costs ($) over 4 L/sec-person	Increased State Revenue to School Districts ($)	Reduced Care-giving by Families ($)
At existing ventilation rate of 4.0 L/sec-person	29 {1.5}	68 {5.2}	3.5 M	1.9 M	0	0	0
From increasing ventilation rate from 4.0 to 7.1 L/s (15 cfm) per person	22 {1.2}	52 {4.3}	2.6 M	1.4 M	4.0 M	33 M	80 M
From increasing ventilation rate from 4.0 to 9.4 L/s (20 cfm)per person	40 {2.1}	92 {7.6}	4.7 M	2.6 M	7.3 M	66 M	160 M

Abbreviations: GWh, gigawatt-hour; M, million;
** 6,224,000 students in 9,900 schools in 2009-10 (from http://www.cde.ca.gov/ls/fa/sf/facts.asp, accessed March 15, 2012)
* percentage of total classroom electricity use
^ percentage of total classroom gas use

FIGURES

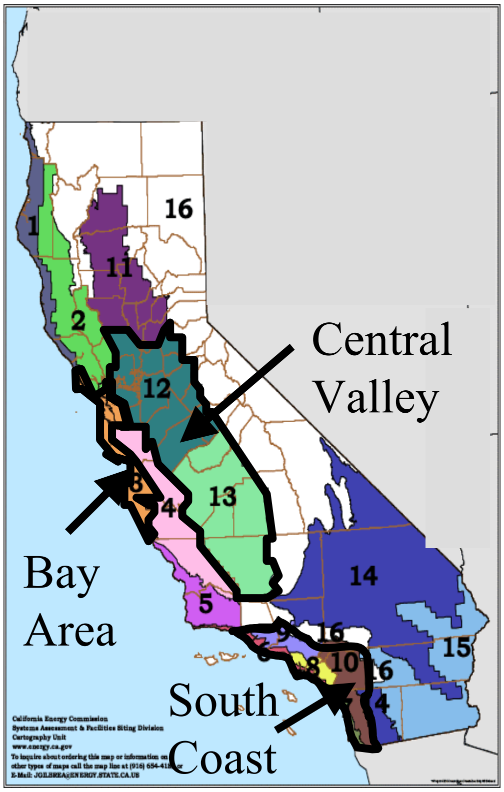
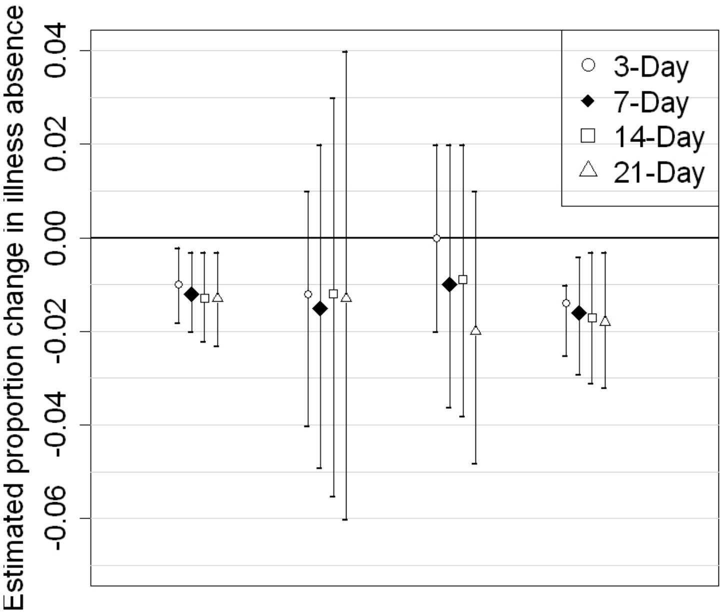


Figure 1. Climate regions included



	South Coast	Bay Area	Central Valley	All
n, range	13,363-14,664	5,252-6,106	9.781-10,438	28,396-31,208

Figure 2. Estimated proportion (%) change in illness absence with increase of 1 L/sec-person of VR, within observed range 1-20 L/sec-person, by district and for combined districts, for four VR-averaging metrics (ventilation-averaging metrics end on day prior to day of illness absence assessment)

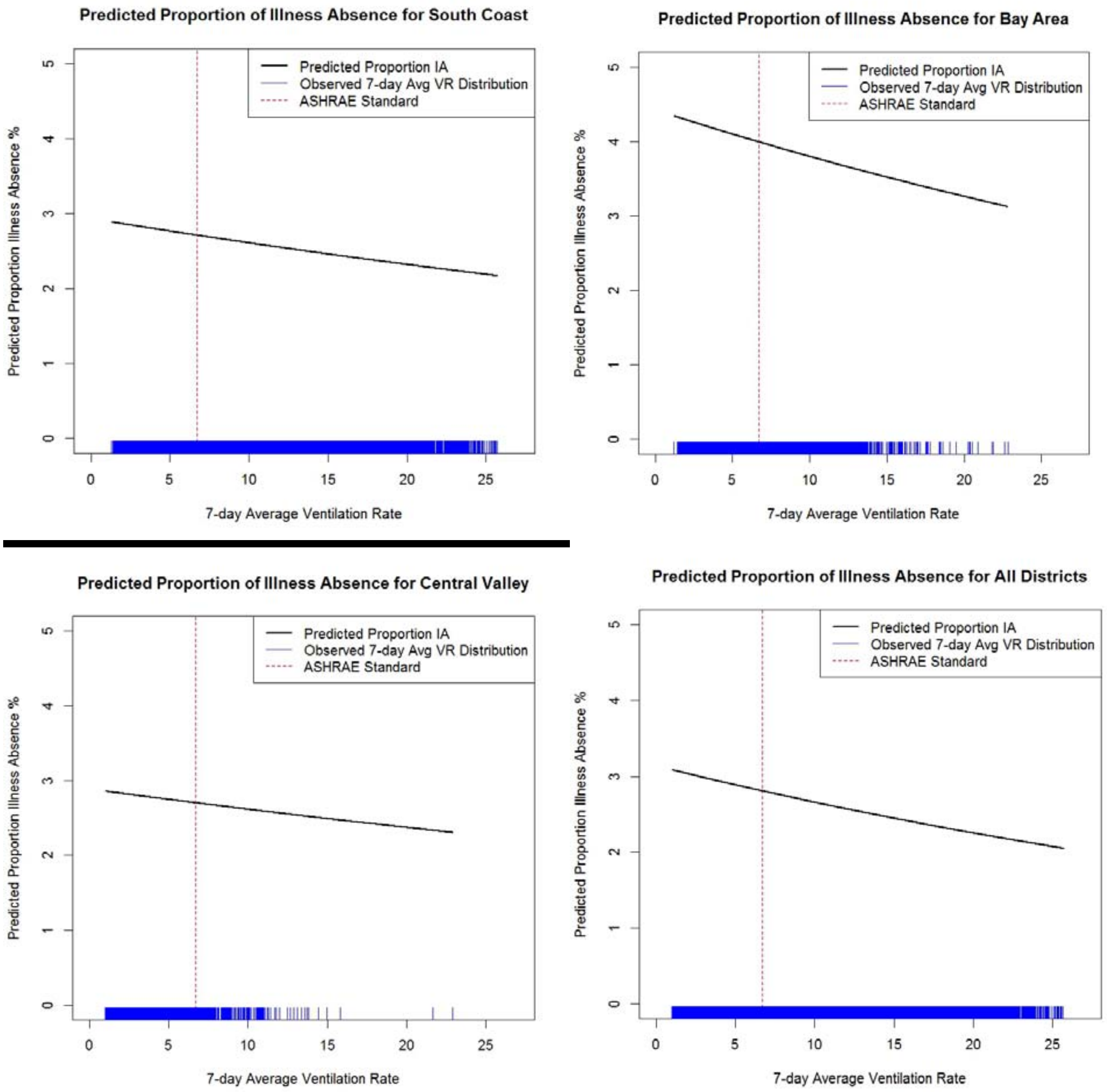


Figure 3. Predicted relationship between ventilation rate and proportion illness absence in three California school districts (Vertical bars at the base of each plot shows the VR values of data points on which that the plot was based. Predicted values are for a standard classroom: 5th grade, with 26 children enrolled, 52% male, 63% participating in the free or reduced price meals program, on a Monday in the non-winter season.**)**

Association of Classroom Ventilation with Reduced Illness Absence: A Prospective Study in California Elementary Schools

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Supporting Information

Contents:..**page**

Data S1. Eligibility Criteria for School Districts, Schools, and Classrooms

Eligible school districts needed to be willing and able to provide us, for students in the studied classrooms, with:

- classroom-level daily illness-related absence data
- classroom-level data for several demographic variables
- individual-level, non-identifiable annual student Math and English standardized test scores (for the current and prior school years).

Eligible *schools* needed to meet the following criteria:

- approval by their Principal to participate;
- approximately six available 3rd, 4th, or 5th grade classrooms, in either permanent or portable buildings, with wired Internet (Ethernet) connections;
- school permission to allow mounting and connection to the Internet of one environmental sensor in each study classroom and one sensor outside at the school, for the duration of the study.

Eligible *classrooms* needed to meet the following criteria:

- single grade 3rd, 4th, or 5th grade classroom;
- students spending most of the day in the same classroom;
- providing a general education, not a dedicated special education, curriculum.

Data S2. Details of data collection process and problems, and related changes in study design

Recruiting of and data collection from school districts

Recruiting the three school districts that met eligibility requirements, including willingness to allow installation of sensors and to provide needed data, was difficult and slow. The first two districts enrolled 12 months later than planned, and the third, 18 months later. Extension of the study an additional year (to include the 2009-10 and 2010-11 school years) largely compensated for this. After establishing participation by the school districts and their selected schools, we installed environmental sensors and contracted with the school districts to provide the needed student data. These arrangements were completed for the SC district by mid-August 2009, the BA district by mid-September 2009, and the CV district by mid-February 2010.

Each school district abstracted the requested student data from their records and provided it to us periodically during the school year. This included classroom enrollment numbers, daily illness absence numbers, and demographic data, either at the classroom level or at the level of unidentified individual students in each classroom. Data for the BA and SC districts were abstracted by the district by programming their electronic databases, whereas for the CV district data were abstracted manually. All districts provided individual-level demographic data, in non-identifiable form, although one district (BA) provided data on lunch program participants at a classroom-aggregate level. All student data were then transmitted to us as electronic spreadsheets.

We had intended to restrict the study to one or two types of ventilation systems in classrooms, so that differences in ventilation type would not complicate the analysis. However, after the difficult process of recruitment for the three enrolled school districts in different climate zones, we found unavoidable differences in ventilation type, some almost completely confounded with school district and climate zone. The BA classrooms included naturally ventilated, mechanically ventilated without air-conditioning, and mechanically ventilated with air-conditioning; the SC classrooms were either naturally or mechanically ventilated but none had air-conditioning; and the CV classrooms all had air-conditioning and mechanical ventilation.

We collected longitudinal data between 2009-2011 on VRs and illness-related absence in approximately 164 classrooms in 28 schools in three school districts. In the CV district, data in the 2009-10 school year were available only for February 2010 on. The following summarizes data provision by school district:

> **SC** (full 2009-10 and 2010-11 school years): received daily data for each classroom on illness absence, total absence, and total enrollment, plus monthly data at a nonidentifiable individual level on requested demographic variables.
>
> **BA** (full 2009-10 and 2010-11 school years): received daily data for each classroom on illness absence (but only when any illness absence reported in the classroom), on total classroom enrollment once each few months (although any classroom reporting an illness absence also reported the enrollment that day), plus data approximately each three months at a nonidentifiable individual level on requested demographic variables.

However, data on participation in the free or reduced price lunch program was provided aggregated at the classroom level.

CV (2009-10 school year beginning only in Feb 2010, and full 2010-11 school years): received daily data for each classroom on illness absence and total enrollment, plus monthly data at the classroom level on requested demographic variables.

Sensor calibration details

- The nondispersive infrared CO_2 sensors had a resolution of 10 ppm, with accuracy (based on calibration by the manufacturer) of the larger of 5% or 100 ppm within the range 0-2,000 ppm, and typically 5% within the range 2,000-5,000 ppm. The sensors also used an auto-calibration feature to prevent drift and maintain calibration over time (ABC Logic^{TM}, described at http://www.telaire.com/refernce/appnotes/abclogic.htm). Each sensor records the low value sensed each day. This is based on the assumption that the unoccupied building each night reaches the outdoor concentration indoors, but excludes values that apparently violate this assumption, requiring outdoor reference values at least three times in the prior 14 days. Each day, if the ABC system detects a significant change up or down of the background reading over the prior 14 days, it slightly adjusts the sensor calibration to return it to the assumed outside level. For this study, the sensors were set to a background outdoor concentration of 380 ppm.

Sensor data problems:

Various problems reduced the amount of sensor information available for analyses:

- *Failure of data transmission from sensors*: Specific Nose sensors, or all Noses at entire schools, sometimes failed to send data, sometimes for weeks or months, leading to substantially fewer classroom days of complete data than expected. We had used these sensors in a prior study with no such problems. This problem was mostly resolved during the latter part of the 2009-10 school year, by resetting some sensors to work with new versions of local server software at schools and by distributing updated "firmware" to the sensors. There were often 5-15 Noses not communicating in each district at any time. The proportion of classroom days with no CO_2 data provided when schools were in session, regardless of whether or not we included the days in the IA analyses (due, for example, to minimum days or other classroom eligibility reasons), were, by district: BA,: 40.4%; SC, 32.1%; and CV, 25.6%. A relatively uncommon additional problem was that students occasionally unplugged Noses (even though plugs were screwed into the outlets), resulting in a few individual Noses going off-line sporadically throughout the school years.
- *Sensor data out of range*: We excluded VR values for classroom days when peak daily CO_2 values were considered out-of-range (i.e., not plausible): under 600 or over 7,000 ppm. The proportions of classroom days with out-of-range values when schools were in session, regardless of whether or not we included the days in the IA analyses (due, for example, to minimum days or other classroom eligibility reasons), were generally low:

  under 600 ppm

BA	1.2%
SC	6.1%
CV	0.3%

over 7,000 ppm
all districts 0.0%.

- *Inaccuracy of outdoor sensors:* The outdoor monitors were installed within cases specially designed for this study, with small fans to provide appropriate air flow-through while protecting from rain. The meters, however, were apparently more sensitive to humidity and temperature extremes than anticipated, as evidenced by the large number of implausible values, ranging from 0-1400 ppm, instead of the expected 380-600 ppm. We excluded measured outdoor CO_2 values from analyses, and estimated all outdoor levels at 400 ppm.

School data problems and exclusions

Various problems reduced the amount of usable data collected:

- *Classroom eligibility changes*: The South Coast district notified us several months into the 2009-10 school year that classroom assignments had been changed after initial sensor installations: 16 monitored classrooms were no longer eligible, because they contained either ineligible grade levels, mixed grades, dedicated special education groups, or non-classroom functions. We relocated 16 monitors to eligible classrooms 3 months into the school year, thus collecting less eligible data than anticipated. In the 2010-11 school year, some classrooms changed use and became ineligible. We changed to eligible classrooms in these schools where possible, but this could not be done in all cases, leading to a small loss in total classroom numbers.
- *Problems with missing illness absence data*: In the BA district, because schools reported illness absences to the school district only on days with non-zero values, missing values and zero values could not be distinguished. Several entire schools had implausibly long periods with zero reported illness absence in any classroom, apparently from non-reporting to the school district, even though these same schools had typical absence patterns for the rest of the school year. We excluded data from an entire school for any period that included no illness absence in all classrooms for 5 or more sequential days, a very unusual event except for these few schools. The SC and CV districts provided data on illness absence for each school day in each classroom, and did not have this problem.
- *Problem with unprocessed illness absence data*: We excluded all data for the entire study from four schools in the BA district that at the end of the school year still had strikingly and implausibly large number of unverified and unexcused absences. As all these values are required to be promptly converted to specific values, these absence data were incompletely processed per district policies, and no usable.
- In the CV district, we excluded data from 4 of 9 schools for the entire 2009-2010 school year, because their manually abstracted data erroneously had omitted a code including several important subsets of illness absence from the totals (e.g., nurse-documented illness absence and doctor’s note for illness absence). These errors were not possible to correct retroactively. All other CV data that year, and all CV data for 2009-10, did include these codes and were included in analyses.

Data S3. Environmental and student covariates

Environmental Covariates

Day of the week was considered to influence the probability of a classroom having any illness absence and also the magnitude of illness absence in a classroom, and was included in both model components as a predictor of IA.

Classroom enrollment count was considered to influence the likelihood of having an infectious agent in the classroom and thus the possibility of any illness absence and also the number of illness absences. It was included in both components of the model.

Winter season is causally related to VRs (see Figure S1 for an extreme example), and was not included in NB models. It was included in ZI models, as it was associated with illness absence, and this model does not include VR. We also ran models with winter season included in the NB models, and estimates were similar except in the SC district models, where it was strongly causally related to VR, and thus inappropriate to include. We thus have reported models without winter season in the NB models.

Outdoor temperature was considered to be causally related to VR, but related to IA only through winter season.

Indoor temperature and relative humidity were assumed to have no relation to VR, but are associated with outdoor temperatures, which are causally related to VR.

Ventilation type was causally related to VR, and assumed not to influence IA except indirectly through different VRs, so it was not included in either model. Ventilation type was also distributed very differently within the districts participating in the study.

Building type was strongly correlated with VR, and was assumed to influence IA only through different VRs, so was not included in models.

Student covariates

Grade level (as a proxy for age), proportion male, and proportion of students in the free/reduced price lunch program, all of which can influence likelihood of illness absence, were included in the NB component in order to reduce unexplained variability. We included participation in free or reduced price meal program, known to be associated with susceptibility to acute lower respiratory tract infections (Graham, 1990), in NB models as an indicator of socioeconomic status.

Race/ethnicity, and English learner, gifted, and special education status were assumed not related to IA beyond any correlation with socioeconomic status, which was represented in model as participation in lunch programs.

References

Graham, N.M. (1990) "The epidemiology of acute respiratory infections in children and adults: a global perspective", *Epidemiologic Reviews*, **12**, 149.

Data S4. Estimation of selected economic benefits from reduced school illness absence

We estimated, for specific changes in VRs, two kinds of potential benefits associated with reduced illness absence. Potential benefits of reduced illness absence from school include, for the school district, increased revenue from the State for student attendance, and possibly decreased illness absence among teachers and staff. Potential benefits for the children and their families include: reduction in suffering and discomfort from illness, risk of subsequent serious or chronic illness, health care costs, and time and costs of caregiving for children at home; While any of these benefits may be substantial, some are difficult to estimate. We estimated only the benefits from decreased illness absence (1) to school districts, of increased revenue from the State for student attendance, and (2) to families, of decreased costs from lost caregiver wages/time.

The State of California funds school districts based not on enrollment but on student attendance, as Actual Daily Attendance (ADA), which excludes any absences. Students generate revenue by contributing to the total ADA for a school year, by equation S4-1:

$$\Sigma R_i = \Sigma\, (ADA_i * R_L) \qquad \text{(S4-1)}$$

where

R_i=revenue generated for district by student (i) during a school year

i ranges from 1 to the total number of students attending school in a district

ADA_i = actual daily attendance for student (i) = total days attended by student (i) in the school year divided by the 180 days of school taught

R_L = revenue limit per ADA ($5,300 per pupil for unified school districts in 2009-10 (although varies by grade level and learning track)

To estimate benefits to families from decreased illness absence due to decreased costs from time taken off work or other tasks to care for their children, we used a previously reported approach based on employment and earnings data in the National Health Interview Survey (NHIS), an annual, nationally representative survey of U.S. households. Levy et al. (2011), using established cost-of-illness methods and NHIS data on children 6-11 years old attending school, and several conservative assumptions, estimated the value of a day for caregiver's time for each child missing school. For employed caregivers, Levy et al. used self-reported daily earnings, or if unemployed, used the value of time for lost household production, according to the cost of hiring someone else to complete the household tasks. This analysis, following Levy, estimates that 69% of the caregivers were employed, with mean annual and daily earnings of $20,087 and $80; and estimates value of household production among unemployed caregivers at $51 daily. The overall averaged value of household production among families with employed or unemployed caregivers was 55.2+15.8 = $71 per day of child illness absence.

References

Levy, D.E., Winickoff, J.P. and Rigotti, N.A. (2011) "School absenteeism among children living with smokers", *Pediatrics*, **128**, 650-656.

Data S5. Calculations and data sources related to increased costs from energy use for specific changes in school VRs

We estimated, for specific changes in VRs, increased costs from energy use. We estimated the annual total (gas and electric) energy use and costs for California classrooms, and the increased energy cost required to raise mean VRs from the current level to 7.1 L/sec-person (15 cfm per person, per California Title 24 ventilation standards), or to 9.4 L/sec-person (20 cfm per person). For information on the current California ventilation standards, see Table S1, and for the comparable ASHRAE standards, Table S2.

The annual amounts of gas and electricity energy used to heat and cool ventilation air supplied to classrooms in California at the estimated existing mean ventilation rate were estimated using equations S5-1 and S5-2:

$$\Delta E = \sum_i E_i \; F_{Ei} \; V \qquad \text{(S5-1)}$$

$$\Delta G = \sum_i G_i F_{Gi} V \qquad \text{(S5-2)}$$

where ΔE is the electricity use for cooling and dehumidifying ventilation air, E_i is the total classroom electricity use for California climate zone i, ΔG is the gas use for heating ventilation air, G_i is the total classroom gas use for climate zone i, F_i and G_i are the fractional change in total classroom electricity and gas use, respectively, use for each 1 L/sec-person change in ventilation rate in climate zone i, and V is the estimated mean ventilation rate of classrooms in California in L/sec-person. Values of E_i and G_i were obtained from the California Energy Use Survey (http://capabilities.itron.com/ceusweb/) and exclude colleges and universities, but include all school floor area (41.4×10^6 m^2), not just the area of classrooms. The coefficient of 0.58 is the ratio of classroom floor area to total floor area for California K-12 schools and yields estimates of energy use applicable to classrooms. The total classroom floor area was based on the product of the average classroom size (89 m^2) and the estimated 268,000 classrooms (Whitmore, 2003). Values of F_{Ei} and F_{Gi} were based on energy simulations (Benne et al., 2009) for the stock of education buildings in U.S. Department of Energy (DOE) climate zones 4B and 4C. Values of F for DOE climate zone 4C were applied to California climate zones FCZ01, FCZ05, FCZ08, and FCZ13, and values of F for for DOE climate zone 4B were applied to the remaining California climate zones. Simulations show that the change in energy use with ventilation rate is approximately linear (Benne, 2009). Thus, values of F_{Ei} and F_{Gi} are not significantly coupled to the ventilation rate or the magnitude of change in ventilation rate. The calculation applies values of F determined for full schools to the classrooms that represent 58% of school floor area.

The value of V was calculated from steady mass balance equation S5-3 relating V with equilibrium indoor carbon dioxide concentration:

$$V = \frac{S}{C_{in} - C_{out}} \quad \text{(S5-3)}$$

where S is the carbon dioxide emission rate per student set equal to 0.0043 L/s (Haverinen-Shaughnessy, 2011), C_{in} is the equilibrium indoor carbon dioxide concentration and C_{out} is the outdoor carbon dioxide concentration. As an estimate of C_{in}, the mean value of the one-hour average highest indoor carbon dioxide concentration from the California Classroom survey (Whitmore, 2003) was used. This survey was designed to provide data representative of the California building stock. Thus, the ventilation rates based on the California Classroom Survey are likely to be more representative of the full stock of California classrooms than the ventilation rates obtained from the sample in the present study. The resulting estimated mean ventilation rate was 4.0 L/s (8.5 cfm) per person.

The same basic equations were used to estimate the increase in gas and electricity use expected if the mean classroom ventilation rates were increased from the estimated current mean value of 4.0 L/s (8.5 cfm) per person to 7.1 L/s (15 cfm) per person as specified in Title 24, or to 9.4 L/s (20 cfm) per person.

The associated annual gas and electricity costs were estimated by multiplying the energy use estimates by California-average gas and electricity prices for commercial building customers. The gas price was \$0.028/kWh (\$0.81 per therm) based on 2010 data from the Energy Information Agency (EIA), and the electricity price was \$0.118/kWh based on data from December 2011 from the EIA.

References

Benne, K., Griffith, B., Long, N., Torcellini, P., Crawley, D. and Logee, T. (2009) Assessment of the energy impacts of outside air in the commercial sector, NREL/TP-550-41955, Golden, CO, National Renewable Energy Laboratory.

Haverinen-Shaughnessy, U., Moschandreas, D.J. and Shaughnessy, R.J. (2011) "Association between substandard classroom ventilation rates and students' academic achievement", *Indoor Air*, **21**, 121-131.

Whitmore, C.A., Clayton, A. and Akland, A. (2003) California Portable Classrooms Study, Phase II: Main Study, Final Report, Volume II., *Report to the California Air Resources Board and California Department of Health Services*, Research Triangle Park, NC, RTI International.

Data S6. Results: estimated benefits and costs of increased VRs in elementary schools

Table S7 provides estimates of the annual energy used to heat and cool ventilation air supplied to California's classrooms with the estimated mean existing ventilation rate of 4.0 L/s (8.5 cfm) per person. The incremental energy needed if mean ventilation rate was increased to 7.1 L/s (15 cfm) per person, as specified in Title 24, or from 7.1 to 9.4 L/s (20 cfm) per person, are also provided, along with estimated annual energy costs. For perspective, in parenthesis the energy consumed for ventilation is provided as a percentage of total building energy use. The calculations indicate that electricity used for ventilation in California classrooms is currently 1.5% of total classroom electricity use, while the gas used for ventilation is 5.2% of total classroom gas use. The associated annual energy costs are $3.5 million for electricity and $1.9 million for gas. Increasing the ventilation rate from 4.0 to 7.1 L/s (15 cfm) per person increases ventilation energy consumption and costs by 75%. Increasing the ventilation rate to 9.4 L/s (20 cfm) per person increases ventilation energy consumption and costs by 135%.

All of the estimates are expected to have a high level of uncertainty. Ventilation rates in the existing stock of schools are estimated based on data from only 67 schools, with data collected only one day per classroom. Also, the model-based estimates of how ventilation rates affect school energy use have not been verified experimentally One cannot directly measure the energy used for ventilation because this energy is just a portion of total energy consumption of the classrooms heating, ventilating, and air conditioning system.

Data S7. Considerations for comparison of current findings to findings of Shendell et al. (2004)

Calculations for comparisons to Shendell et al. (2004)

Shendell et al. (2004) reported that higher classroom VRs were associated with a substantial reduction in student absence: a decrease of 1,000 ppm in indoor minus outdoor CO_2 concentrations (ΔCO_2) within the observed range of 10-4,200 ppm was associated with a 10% to 20% relative decrease (0.5-0.9% absolute decrease) in *total* student absence (which averaged 5.0%). This equals a 1% to 2% relative decrease (0.05-0.09% absolute decrease) in total student absence per decrease of 100 ppm ΔCO_2. This in turn is equivalent (see http://www.iaqscience.lbl.gov/si/vent-absences.html) to a relative decrease of 1-4% (absolute decrease of 0.05-1.8%) in total absence, per each additional 1 L/sec-person in VR within the range of 2.5-15 L/sec-person. We assume that all this decrease in total absence is within illness absence rather than in other types of absence, and that the mean illness absence is the 2.35% observed in the present study. The 0.05-0.18% absolute decrease in illness absence is then an estimated 2.1-7.6% relative decrease in illness absence, per VR increase of 1 L/sec-person, in the range of 2.5-15 L/sec-person.

This estimated finding of an equivalent 2.1-7.6% relative decrease in illness absence per VR increase of 1 L/sec-person is approximately 2.1-5.1 times larger than the findings in the present study of a 1.0 to 1.5% relative decrease (for the 7-day averaged VR metric).

Quality of measurements of ventilation and illness absence in Shendell et al. (2004)

Measurements of the two primary variables were crude: one-time spot measurements of CO_2 for at most 5 minutes within and outside each classroom as an indicator for classroom VRs throughout a school year, and annual average rates of total classroom absence, which included illness absence but also other absence unlikely to be influenced by VR.

In theory, VR is correlated with equilibrium ΔCO_2 concentrations, and would only correlate with randomly measured ΔCO_2 values to the extent that these happened to correlate with equilibrium CO_2 concentrations. The equilibrium CO_2 concentration is reached in an indoor space only after a sufficient period of constant occupancy and ventilation. Using ΔCO_2 measurements for classrooms made at random times as proxies for the equilibrium values for CO_2 will result in underestimation of equilibrium ΔCO_2 and thus overestimation of VRs in the study. This will cause “nondifferential misclassification” of the VRs, likely to cause *underestimation* of any true relationships of health effects with VR. In addition, Shendell et al. used the outcome of total absence, much of which would not be expected to vary with VR, so that any true impact of VR on illness absence would be diluted by unrelated absences within the larger category of total absence.

References

Shendell, D.G., Prill, R., Fisk, W.J., Apte, M.G., Blake, D. and Faulkner, D. (2004) "Associations between classroom CO_2 concentrations and student attendance in Washington and Idaho", *Indoor Air*, **14**, 333-341.

Table S1. Current ventilation standards per State of California*

2008 Building Energy Efficiency Standards
CALIFORNIA CODE OF REGULATIONS, TITLE 24, Part 6
SUBCHAPTER 3: SECTION 121 – REQUIREMENTS FOR VENTILATION, p. 73.

(b) **Design Requirements for Minimum Quantities of Outdoor Air**. Every space in a building shall be designed to have outdoor air ventilation according to Item 1 or 2 below:

> 1. **Natural ventilation**. A. Naturally ventilated spaces shall be permanently open to and within 20 feet of operable wall or roof openings to the outdoors, the openable area of which is not less than 5 percent of the conditioned floor area of the naturally ventilated space. Where openings are covered with louvers or otherwise obstructed, openable area shall be based on the free unobstructed area through the opening. . . .
> 2. **Mechanical ventilation**. Each space that is not naturally ventilated under Item 1 above shall be ventilated with a mechanical system capable of providing an outdoor air rate no less than the larger of: A. The conditioned floor area of the space times the applicable ventilation rate from TABLE 121-A (of 0.15 cfm/ft2); or B. 15 cfm per person times the expected number of occupants.

Note: This California ventilation standard for classrooms specifies a ventilation rate between the two default ASHRAE standards applicable to elementary school classrooms (Table SM-1b below).

*Source: http://www.energy.ca.gov/2008publications/CEC-400-2008-001/CEC-400-2008-001-CMF.PDF Accessed April 14, 2012

Table S2. Current ASHRAE ventilation rate requirements (ASHRAE 2010, p. 12)

	ASHRAE 62.1-2010		
Space Use	**VR/person**	**VR/area**	**Overall, at specific assumed occupant density**
Classrooms (ages 5-8)	5 L/s-person (10 cfm/person)	0.6 L/s-m2 (0.12 cfm/ft2)	7.4 L/sec-person* {assumed 25 persons/100 m^2} (15 (14.8) cfm/person)* {assumed 25 persons/1000 ft^2}
Classrooms (ages 9+)	5 L/s-person (10 cfm/person)	0.6 L/s-m2 (0.12 cfm/ft2)	6.7 L/sec-person ** {assumed 35 persons/100 m^2} (13 (13.4) cfm/person)** {assumed 35 persons/1000 ft^2)

* assumed classroom occupant density =25 persons/100 m^2 or /1,000 ft^2

** assumed classroom occupant density = 35 persons/100 m^2 or /1,000 ft^2 , but 100 m^2 =1,076 ft^2

Note: Children in third grade are usually ages 8 or 9 (or sometimes 7). Children in 4th and 5th grades will usually be ages 9+.

Source**:** ASHRAE (2010) ANSI/ASHRAE Standard 62.1-2010: Ventilation for Acceptable Indoor Air Quality, Atlanta, GA, US, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc

Table S3. Unadjusted IRR estimates* and 95% confidence intervals (CI) from zero inflated negative binomial models for association between classroom ventilation rate (VR) metrics and daily classroom proportion of illness absence, per increase of 1 L/sec-person VR in observed range of 1-20 L/sec-person**

	South Coast District			Bay Area District			Central Valley District			All Districts		
VR averaging period	n	IRR	(95% CI**) p-value	n	IRR	(95% CI**) p-value	n	IRR	(95% CI**) p-value	n	IRR	(95% CI**) p-value
3 days***	13,363	0.988	(0.980-0.997) p=0.009	5,252	0.979	0.907-1.06 p=0.59	9,781	0.998	(0.979-1.02) p=0.81	28,396	0.988	(0.978-0.997) p=0.011
7 days***	14,318	0.986	(0.975-0.996) p=0.008	5,742	0.974	0.889-1.07 p=0.58	10,120	0.987	(0.965-1.01) p=0.26	30,180	0.985	(0.974-0.996) p=0.007
14 days***	14,559	0.984	(0.973-0.996) p=0.008	5,955	0.978	0.876-1.09 p=0.70	10,378	0.989	(0.962-1.02) p=0.43	30,892	0.985	(0.973-0.996) p=0.009
21 days***	14,664	0.984	(0.973-0.996) p=0.008	6,106	0.978	0.866-1.10 p=0.72	10,438	0.980	(0.954-1.01) p=0.14	31,208	0.984	(0.972-0.996) p=0.008

Abbreviations: IRR, incidence rate ratio; L, liter; s, second; VR, ventilation rate

* estimates are the relative (multiplicative) change in the outcome for each increase of one L/sec-person

** bootstrapped

** ending on day prior to day on which illness absence assessed

Table S4. Alternate adjusted IRR estimates* and 95% confidence intervals (CI) from zero inflated negative binomial models*** for association between single-day classroom ventilation rate (VR) and period-averaged daily classroom proportion of illness absence, per increase of 1 L/sec-person VR in observed range of 1-20 L/sec-person (note – none of models producing these estimates converged, so estimates may not be meaningful)**

VR averaging period	Type of Model	South Coast District		Bay Area District		Central Valley District		All Districts	
		IRR*	(95% CI**) p-value	IRR*	(95% CI**) p-value	IRR*	(95% CI**) p-value	IRR*	(95% CI**) p-value
7 days****	Zero-Inflated Negative Binomial	0.986+	(0.977-0.994) p=0.001	0.995	(0.961,1.031) p=0.789	0.986	(0.967-1.004) p=0.123	0.978+	(0.962-0.994) p=0.007
21 days****	Negative Binomial	0.987+	(0.978-0.996) p=0.005	0.999	(0.930-1.073) p=0.983	0.974+	(0.950-0.999) p=0.043	0.976+	(0.957-0.996) p=0.017

Abbreviations: IRR, incidence rate ratio; L, liter; s, second; VR, ventilation rate

* estimates are the relative (multiplicative) change in the outcome for each increase of one L/sec-person

** bootstrapped

***winter season included in the zero inflation component of ZINB models, but not the main component of ZINB or NB models; all models contained total classroom demographics count as an estimate of total enrollment

**** ending on day prior to day on which illness absence averaging period began

+ p-value <0.05

Table S5. Predicted proportion of illness absence at specified outdoor air ventilation rates, based on adjusted models* using 7-day averaged ventilation rates, in three California climate zones

Ventilation Rates		Notes	Predicted proportion of illness absence			
(L/sec-person)	(cfm per person)		SC District	BA District	CV District	All Districts
1.0	2.1		0.029	0.043	0.029	0.031
4.0	8.5	estimated mean VR for California K-12 classrooms (see Appendix 2)	0.028	0.042	0.028	0.029
5.0	10.6		0.028	0.041	0.027	0.029
6.7	13, 13.4, 14.2 **	ASHRAE default standard for classrooms ages 9+ (includes grade 4-5); assumes occupancy of 35 persons/100 m^2 **	0.027	0.040	0.027	0.028
7.1	15	minimum VR for classrooms specified in California Title 24	0.027	0.040	0.027	0.028
7.4	15, 14.8, 15.7***	ASHRAE default standard for classrooms ages 5-8 (includes grade 3); assumes occupancy of 25 persons/100 m^2 **	0.027	0.040	0.027	0.027
9.4	20	minimum VR specified for offices in ASHRAE 62-89 in 1989	0.026	0.038	0.026	0.027
10.0	21.2		0.026	0.038	0.026	0.027
15.0	31.8		0.025	0.035	0.025	0.024
20.0	42.4	This estimate has greater uncertainty, as 20 L/sec/person was the 95th percentile of the observed range in one district, and not included at all in the other two districts.	0.023	0.033	0.024	0.023

Abbreviations: VR, ventilation rate

* assuming specific mix of personal and building covariates: 26 children enrolled in each classroom who were in 5th grade, 52% male, 63% participating in the free or reduced price meals program, on a Monday in the non-winter season.

** 13 cfm per person is the nominal ASHRAE default standard for classrooms ages 9+, assuming occupancy of 35 persons/1,000 ft^2; 13.4 is the as-calculated value based on this occupant density; 14.2 would be an exact conversion from the standard in SI units, because 100 m^2 = 1,076 ft^2

*** 15 cfm per person is the nominal ASHRAE default standard for classrooms ages 5-8, assuming occupancy of 25 persons/1,000 ft^2; 14.8 is the as-calculated value of 14.8 based on this occupant density; 15.7 would be an exact conversion from the standard in SI units, because 100 m^2 = 1,076 ft^2

Table S6. Estimated losses in revenue to school districts (based on Equation S4-1)

Ventilation rate	Estimated decrease in illness absence proportion (%)	Average decrease in annual illness days per student	Predicted increase in ADA revenue per student	Predicted increase in ADA revenue per 1,000 students
4.0 to 7.1 L/sec-person	0.1%	0.18	$5.30	$5,300
4.0 to 9.4 L/sec-person	0.2%	0.36	$10.60	$10,600

Abbreviations: ADA, Actual Daily Attendance
* based on estimates from combined student model with 7-day averaged VR metric, a 180-day school year, and $5,300/year in ADA reimbursement per child

Table S7. Estimates of the energy use and costs for cooling and heating the ventilation air provided to Classrooms in California.

	Electricity Use (GWh) (%)*	Gas Use (GWh) (%)^	Electricity Costs ($)	Gas Costs ($)
At existing ventilation rate of 4.0 L/s (8.5 cfm) per person	29 (1.5)	68 (5.2)	3.5 x 10^6	1.9 x 10^6
From increasing ventilation rate from 4.0 to 7.1 L/s (8.5 to 15 cfm) per person	22 (1.2)	52 (4.3)	2.6 x 10^6	1.4 x 10^6
From increasing ventilation rate from 4.0 to 9.4 L/s (8.5 to 20 cfm) per person	40 (2.1)	92 (7.6)	4.7 x 10^6	2.6 x 10^6

*percentage of total classroom electricity use

^percentage of total classroom gas use

Figure S1. Average annual ventilation rates in naturally ventilation classrooms – an example of why annual average ventilation rates may be a poor proxy for daily exposure in these classrooms, and winter season may be causally linked to classroom ventilation rates