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Association of classroom ventilation with reduced illness absence: a prospective study in California elementary schools

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 two year daily real-time carbon dioxide in each classroom) 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/s-person California standard. For each additional 1 l/s-person of VR, IA was reduced significantly ($p<0.05$) in models for combined districts (−1.6%) and for SC (−1.2%), and nonsignificantly 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/s-person) to the State standard would decrease IA by 3.4%, increase attendance-linked funding to schools by $33 million annually, and increase costs by 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.

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

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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 ensure that ventilation rates 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.

Nomenclature

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
ΔCO_2	indoor minus outdoor CO_2 concentrations

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 whether 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 et al., 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 Figure 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 online 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. We

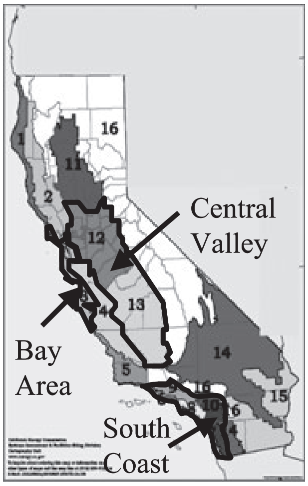

Fig. 1 California climate regions included

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 × 4 × 8 in) Web/Ethernet-connected environmental sensor (the 'Nose'™ by PureChoice). The sensors transmitted data to the manufacturer for two years, as 5-min averaged values of CO_2 concentration (in parts per million, ppm), temperature (in degrees Fahrenheit, °F), 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 0–2000 ppm, and typically 5% within the range 2000–5000 ppm. The sensors also used a daily autocalibration process to prevent drift and maintain calibration over time (details provided in Data S2). Custom-built protective housings were provided to protect CO_2 sensors located outdoors from excessive moisture. Our computer server downloaded data from the PureChoice server daily for two years. 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/s-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-min moving average of indoor CO_2 values between 7 a.m. and 3 p.m. each day. The corresponding outside CO_2 concentration, originally planned to be the 60-min outdoor averaged CO_2 for the period ending at the midpoint of the selected 15-min 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 airflow rate per person (l/s-person)

N = CO_2 generation rate per person (see Note)

C_{max15} = maximum 15-min 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 – 1 day to 3 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 et al., 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 et al., 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 7000 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/s-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 inflated (ZI) model to estimate the probability of each observation to be nonzero and a negative binomial (NB) model to estimate the values of those observations with a nonzero 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, resampling 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 to be 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/s-person, respectively. VRs varied most in the SC district, less in the BA, and relatively little in the CV,

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)[a]	50–63; 65–74	47–59; 56–78	42–67; 56–99	—
Ranges of monthly mean outdoor relative humidities (2010)[a]	56–77%	64–87%	36–83%	—
Median (5th%, 95th%) of daily average indoor temperatures in °F[b]	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	0.59 (35)	0.81 (42)	0.59 (30)	66% (107)
Proportion (number) in portable buildings	0.41 (24)	0.19 (10)	0.41 (21)	34% (55)
Ventilation type for classrooms				
Proportion (number) with natural ventilation	0.76 (45)	0.31 (16)	0.00 (0)	37% (61)
Proportion (number) with mechanical ventilation, no AC	0.24 (14)	0.31 (16)	0.00 (0)	19% (30)
Proportion (number) with AC	0.00 (0)	0.38 (20)	1.00 (51)	44% (71)
Number of classroom days with ventilation rate data[c]	11 069	9615	8135	28 819
Approximate total enrollment in all 3rd-, 4th-, and 5th-grade classrooms in studied school districts[d]	30 000	12 000	3000	45 000

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

s.d. = 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.

[a] For same or nearby city in that climate region of California.

[b] 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.

[c] Includes all those with valid VR data, although may not all be included in models; that is, it includes all 28 schools and 162 classrooms, even though some classrooms, or entire schools in BA, were excluded from analyses.

[d] Regardless of whether classrooms included in this study; numbers rounded to nearest 1000; data from California Department of Education (2012a).

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

	Peak (estimated equilibrium) CO_2 concentration (ppm)[b]							VR (l/s-person)[b]						
	5th % ile	25th %ile	50th %ile	75th %ile	95th %ile	Mean	s.d.	5th %ile	25th %ile	50th %ile	75th %ile	95th %ile	Mean	s.d.
School district														
SC	654	853	1140	1700	2640	1350	652	2.31	3.98	7.01	11.40	20.30	8.43	5.53
BA	769	1040	1400	2040	3220	1630	770	1.83	3.15	5.14	8.08	14.00	6.17	4.03
CV	1200	1850	2380	3030	4170	2490	901	1.37	1.97	2.61	3.55	6.43	3.11	2.01
Building type														
Permanent	702	984	1390	2000	3020	1570	734	1.97	3.23	5.24	8.84	17.10	6.77	4.80
Portable	750	1260	2060	2880	4080	2160	1060	1.40	2.09	3.12	6.03	14.80	4.98	4.53
Ventilation type														
Natural	695	914	1270	1813	2760	1450	672	2.19	3.66	5.95	10.10	17.50	7.42	4.91
Mechanical/no AC	650	848	1080	1420	2230	1200	485	2.83	5.05	7.56	11.50	20.60	8.98	5.31
AC	1010	1700	2280	2950	3990	2370	916	1.44	2.03	2.75	3.99	8.50	3.51	2.50

AC, air-conditioning; BA, Bay Area; CV, Central Valley; SC, South Coast; s.d., standard deviation; VR, ventilation rate.

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

[b] Because peak indoor CO_2 concentrations below 600 ppm and above 7000 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/s-person).

with ranges between the 5th and 95th percentiles for VR of 18.0, 12.2, and 5.1 l/s-person, respectively. VRs also varied by building type, with medians in permanent and portable classrooms of 5.2 and 3.1 l/s-person, respectively, and by ventilation type, with medians for natural, mechanical/no AC, and AC of 6.0, 7.6, and 2.8 l/s-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

Table 3 Demographic and illness absence data, for classrooms and times with student data eligible for analyses[a]

	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 (s.d.)	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	1401	561	1089	2358
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[b]	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[a]	16 807	7338	10 562	34 707
Mean daily classroom proportion (%) of illness absence (s.d.)	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[c]	2.84	2.32	2.95	2.75
Nonwinter season	2.19	2.02	2.40	2.22

s.d., standard deviation.

[a] Based on all valid IA data eligible for inclusion in models, from 136 out of 162 classrooms described in Table 1; however, some classroom days included in these data were not included in models if lacking necessary VR data.

[b] Official name of the national free or reduced price lunch program.

[c] Winter was defined as the months of December, January, and February.

1 year (Data S2). Average enrollment totaled across all studied classrooms during the study was 2358. 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 with 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 to 2.53% and across grades from 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 from ZINB models, as incidence rate ratios (IRRs) and 95% confidence intervals (CIs), 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 nonlinear 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 that if a classroom were to increase its VR by 1 l/s-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/s-person) are estimated by exponentiating the estimates accordingly.

Table 4 Adjusted IRR estimates[a] and 95% confidence intervals (CI)[b] 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/s-person VR in observed range of 1–20 l/s-person

	SC district			BA district			CV district			All districts		
VR averaging period	*n*	IRR	(95% CI[b]) *P*-value	*n*	IRR	(95% CI[b]) *P*-value	*n*	IRR	(95% CI[b]) *P*-value	*n*	IRR	(95% CI[b]) *P*-value
3 days[c]	13 363	0.990	(0.982–0.998) $P = 0.01$	5252	0.988	0.963–1.01 $P = 0.38$	9781	1.000	(0.980–1.02) $P = 1.0$	28 396	0.986	(0.975–0.997) $P = 0.01$
7 days[c]	14 318	0.988	(0.980–0.997) $P = 0.01$	5742	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[c]	14 559	0.987	(0.978–0.997) $P = 0.008$	5955	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[c]	14 664	0.987	(0.977–0.997) $P = 0.01$	6106	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) $P = 0.02$

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

[a] Estimates are the relative (multiplicative) change in the outcome for each increase of 1 l/s-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).

[b] Bootstrapped.

[c] Ending on day prior to day on which illness absence assessed.

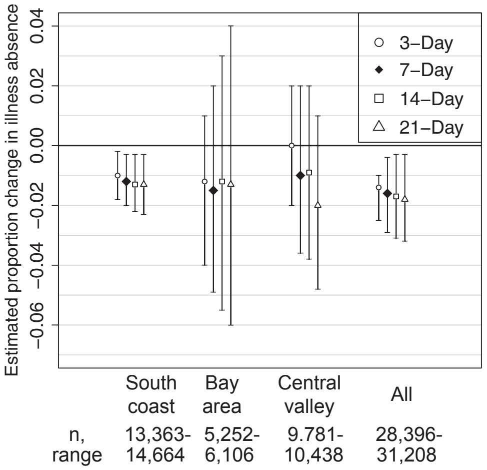

Fig. 2 Estimated proportion (%) change in illness absence with increase of 1 l/s-person of VR, within observed range 1–20 l/s-person, by district and for combined districts, for four VR-averaging metrics (ventilation-averaging metrics end on day prior to day of illness absence assessment)

Based on these modeled estimates, for each additional 1 l/s-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 1 l/s-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 in the other districts, and higher proportion with free or reduced price meals was significantly associated with reduced illness absence in SC, but not in 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 inflated 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/s-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 (Figure 3).

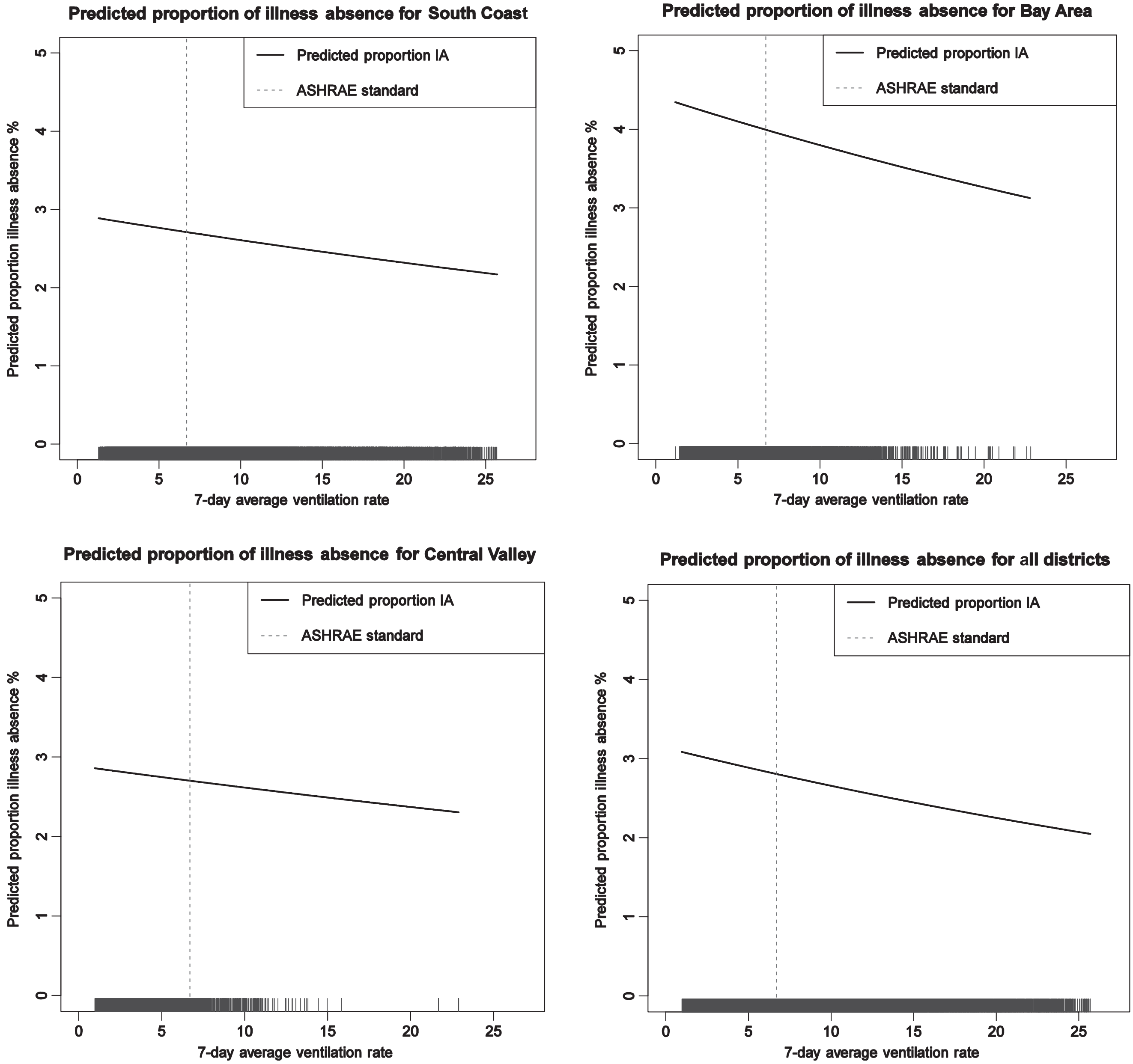

Fig. 3 Predicted relationship between ventilation rate and proportion illness absence in three California school districts (vertical bars at the base of each plot show the VR values of data points on which that plot was based. Predicted values are for a standard classroom: 5th grade, with 26 children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

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/s-person to 7.1 l/s-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/s-person would lead to 7–10% predicted relative reductions in IA; VRs increased to 15 l/s-person, an 11–17% reduction.

Benefits and costs of increased VRs in elementary schools

Estimated loss 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 1000 students (Data S4). With mean VR increased from 4.0 to 7.1 or to 9.4 l/s-person, predicted increases in ADA revenue (Table S6) are \$5300 and \$10 600, respectively, per 1000 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 1000 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 9900 schools in 2009–2010) (California Department of Education, 2012b), an increase in mean VRs from 4 to 7.1 l/s-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/s-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/s-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/s-person. Total estimated benefits from VRs increased to 7.1 l/s-person are \$113 million, over 25 times the estimated costs of 4.0 million. Total benefits from an increase to 9.4 l/s-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/s-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/s-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/s-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/s-person increase in VRs between 12 and 24 l/s-person. The effect seen in the present study, a 1.0–1.5%

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

	Energy use		Costs			Benefits	
	Electricity use (GWh) [% of total][b]	Gas use (GWh) [% of total][c]	Electricity costs (\$)	Gas costs (\$)	Total increase in energy costs (\$) over 4 l/s-person	Increased state revenue to school districts (\$)	Reduced caregiving by families (\$)
At existing ventilation rate of 4.0 l/s-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

GWh, gigawatt-hour; M, million.

[a] 6 224 000 students in 9900 schools in 2009–2010 (from http://www.cde.ca.gov/ls/fa/sf/facts.asp, accessed March 15, 2012).

[b] Percentage of total classroom electricity use.

[c] Percentage of total classroom gas use.

reduction in IA per 1 l/s-person increase in VRs between approximately 2–20 l/s-person, is less than half as large. Myatt et al. (2002), however, found no difference in illness absence in offices at two very high levels of VR (between 40 and 45 l/s-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 US schools in Washington and Idaho. Higher classroom VRs were associated with substantially reduced student absence: a decrease of 1000 ppm in indoor minus outdoor CO_2 concentrations (ΔCO_2) within the range of 10–4200 ppm was associated with a 10–20% 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/s-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 their 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 biologic and nonbiologic 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 et al., 2007; Milton et al., 2000; Riley et al., 1978; Riley, 1982; Rudnick and Milton, 2003; Sun et al., 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 et al., 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 et al., 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 1000 ppm, implying ventilation rates < 7.4 l/s-person (Daisey et al., 2003). Ventilation rates in 45–88% of US public elementary school classrooms were less than specified in codes (California Air Resources Board, 2004; Corsi et al., 2002; Haverinen-Shaughnessy et al., 2011; Shaughnessy et al., 2006; Shendell et al., 2004). Peak CO_2 concentrations exceeded 3,000 in 21% of Texas elementary school classrooms (Corsi et al., 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 et al., 2004). Portable classrooms in Idaho had median indoor CO_2 concentrations of 1590 ppm vs. 670 ppm for permanent classrooms (Shendell et al., 2004).

Strengths and limitations of study

This is the largest US 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 to 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 midstudy, 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 to 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 1400 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 less than 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-min 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 effects 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 with 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 a 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 et al., 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 nonlinear 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 three 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 of increased VRs 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 schoolchildren 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 USA, and increasing ventilation rates may be more costly in the Midwest or Northeast USA due to extreme temperatures, or in the Southeast USA 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/s-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. If chronic exposures to indoor contaminants such as chemicals can increase 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 attempts 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/s-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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Competing financial interests declaration

The authors declare that they have no competing financial interests.

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).

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.

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/s-person VR in observed range of 1–20 l/s-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/s-person VR in observed range of 1–20 l/s-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.

References

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.

Bendrick, G.A. (1998) Seasonal variation of grounding rates among B-52H aircrew, *Mil. Med.*, **163**, 692–694.

Brundage, J.F., Scott, R.M., Lednar, W.M., Smith, D.W. and Miller, R.N. (1988) Building-associated risk of febrile acute respiratory diseases in Army trainees, *JAMA*, **259**, 2108–2112.

California Air Resources Board (2004) *Report to the California Legislature: Environmental Health Conditions in California's Portable classrooms*, Sacramento, CA, California Air Resources Board and California Department of Health Services.

California Department of Education (2008) Categorical Allocations & Audit Resolution, School Fiscal Services Division of the California Department of Education, Vol. 2008.

California Department of Education (2012a) Ed-Data: Fiscal, Demographic, and Performance Data on California's K-12 Schools, Vol. 2012.

California Department of Education (2012b) School Facilities Fingertip Facts, Vol. 2012.

California Energy Commission (2008) California Energy Maps: California Building Climate Zone Map, Vol. 2008.

Corsi, R.L., Torres, V.M., Sanders, M. and Kinney, K.L. (2002) Carbon dioxide levels and dynamics in elementary schools: results of the TESIAS Study. In: Proceedings of Indoor Air '02: Proceedings of the 9th International Conference on Indoor Air Quality and Climate, Vol. 2, pp. 74–79.

Daisey, J.M., Angell, W.J. and Apte, M.G. (2003) Indoor air quality, ventilation and health symptoms in schools: an analysis of existing information, *Indoor Air*, **13**, 53–64.

Erdmann, C.A. and Apte, M.G. (2004) Mucous membrane and lower respiratory building related symptoms in relation to indoor carbon dioxide concentrations in the 100-building BASE dataset, *Indoor Air*, **14**, 127–134.

Godwin, C. and Batterman, S. (2007) Indoor air quality in Michigan schools, *Indoor Air*, **17**, 109–121.

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.

Klepeis, N.E., Tsang, A.M. and Behar, J.V. (1996) *Analysis of the National Human Activity Pattern Survey (NHAPS) Respondents from a Standpoint of Exposure Assessment - Final EPA Report*, Washington, DC, U.S. EPA.

Lessler, J., Reich, N.G., Brookmeyer, R., Perl, T.M., Nelson, K.E. and Cummings, D.A.T. (2009) Incubation periods of acute respiratory viral infections: a systematic review, *Lancet. Infect. Dis.*, **9**, 291–300.

Li, Y., Leung, G.M., Tang, J.W., Yang, X., Chao, C.Y.H., Lin, J.Z., Lu, J.W., Nielsen, P.V., Niu, J., Qian, H., Sleigh, A.C., Su, H.J.J., Sundell, J., Wong, T.W. and Yuen, P.L. (2007) Role of ventilation in airborne transmission of infectious agents in the built environment - a multidisciplinary systematic review, *Indoor Air*, **17**, 2–18.

Milton, D.K., Glencross, P.M. and Walters, M.D. (2000) Risk of sick leave associated with outdoor air supply rate, humidification, and occupant complaints, *Indoor Air*, **10**, 212–221.

Myatt, T.A., Staudenmayer, J., Adams, K., Walters, M., Rudnick, S.N. and Milton, D.K. (2002) A study of indoor carbon dioxide levels and sick leave among office workers, *Environ. Health*, **1**, 3–12.

Nichol, K.L., Lind, A., Margolis, K.L., Murdoch, M., Mcfadden, R., Hauge, M., Magnan, S. and Drake, M. (1995) The effectiveness of vaccination against influenza in healthy, working adults, *N. Engl. J. Med.*, **333**, 889–893.

Riley, R.L. (1982) Indoor airborne infection, *Environ. Int.*, **8**, 317–320.

Riley, E.C., Murphy, G. and Riley, R.L. (1978) Airborne spread of measles in a suburban elementary school, *Am. J. Epidemiol.*, **107**, 421–432.

Rudnick, S.N. and Milton, D.K. (2003) Risk of indoor airborne infection transmission estimated from carbon dioxide concentration, *Indoor Air*, **13**, 237–245.

Seppanen, O., Fisk, W.J. and Mendell, M.J. (1999) Association of ventilation rates and CO_2 concentrations with health and other responses in commercial and institutional buildings, *Indoor Air*, **9**, 226–252.

Shaughnessy, R.J., Haverinen-Shaughnessy, U., Nevalainen, A. and Moschandreas, D. (2006) A preliminary study on the association between ventilation rates in classrooms and student performance, *Indoor Air*, **16**, 465–468.

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.

Simoni, M., Cai, G.H., Norback, D., Annesi-Maesano, I., Lavaud, F., Sigsgaard, T., Wieslander, G., Nystad, W., Canciani, M. and Viegi, G. (2011) Total viable molds and fungal DNA in classrooms and association with respiratory health and pulmonary function of European schoolchildren, *Pediatr. Allergy Immunol.*, **22**, 843–852.

Sun, Y., Wang, Z., Zhang, Y. and Sundell, J. (2011) In China, students in crowded dormitories with a low ventilation rate have more common colds: evidence for airborne transmission, *PLoS ONE*, **6**, e27140.

Sundell, J., Levin, H., Nazaroff, W.W., Cain, W.S., Fisk, W.J., Grimsrud, D.T., Gyntelberg, F., Li, Y., Persily, A.K., Pickering, A.C., Samet, J.M., Spengler, J.D., Taylor, S.T. and Weschler, C.J. (2011) Ventilation rates and health: multidisciplinary review of the scientific literature, *Indoor Air*, **21**, 191–204.

Wargocki, P., Sundell, J., Bischof, W., Brundrett, G., Fanger, P.O., Gyntelberg, F., Hanssen, S.O., Harrison, P., Pickering, A., Seppanen, O. and Wouters, P. (2002) Ventilation and health in non-industrial indoor environments: report from a European multidisciplinary scientific consensus meeting (EUROVEN), *Indoor Air*, **12**, 113–128.

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.*

Yau, K.K.W., Wang, K. and Lee, A.H. (2003) Zero-inflated negative binomial mixed regression modeling of over-dispersed count data with extra zeros, *Biomed. J.*, **45**, 437–452.