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A Prospective Study of Ventilation Rates and Illness Absence in California Office Buildings

Mark J. Mendell
Ekaterina A. Eliseeva
Michael Spears
Wanyu R. Chan
Sebastian Cohn
Douglas P. Sullivan
William J. Fisk

Environmental Energy Technologies Division

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Disclaimer

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Environmental Energy Technologies Division

Energy Analysis and Environmental Impacts Department

Indoor Environment Group

1 Cyclotron Road, B90-R3058

Lawrence Berkeley National Laboratory

Berkeley, CA 94720

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Abstract

Background – This study investigated the associations of ventilation rates (VRs), estimated from indoor CO_2 concentrations, in offices with the amount of respiratory infections, illness absences, and building-related health symptoms in occupants.
Methods – Office buildings were recruited from three California climate zones. In one or more study spaces within each building, real-time logging sensors measured carbon dioxide, temperature, and relative humidity for one year. Ventilation rates were estimated using daily peak CO_2 levels, and also using an alternative metric. Data on occupants and health outcomes were collected through web-based surveys every three months. Multivariate models were used to assess relationships between metrics of ventilation rate or CO_2 and occupant outcomes. For all outcomes, negative associations were hypothesized with VR metrics, and positive associations with CO_2 metrics.
Results – Difficulty recruiting buildings and low survey response limited sample size and study power. In 16 studied spaces within 9 office buildings, VRs were uniformly high over the year, from twice to over nine times the California office VR standard (7 L/s or 15 cfm per person). VR and CO_2 metrics had no statistically significant relationships with occupant outcomes, except for a small significantly positive association of the alternative VR metric with respiratory illness-related absence, contrary to hypotheses.
Conclusions– The very high time-averaged VRs in the California office buildings studied presumably resulted from "economizer cycles" bringing in large volumes of outdoor air; however, in almost all buildings even the estimated minimum VRs supplied (without the economizer) substantially exceeded the minimum required VR. These high VRs may explain the absence of hypothesized relationships with occupant outcomes. Among uniformly high VRs, little variation in contaminant concentration and occupant effects would be expected. These findings may provide initial evidence for an upper bound of the range of VRs within which increased VRs provide benefits in reducing illness absence.

Keywords (3-10)
Ventilation rate, IAQ, SBS, illness absence

Background

The primary goal of this study was to provide quantitative estimates of the association between ventilation rates (VRs) in offices and adverse effects on building occupants – primarily respiratory illnesses and illness-related absences from work, but also acute health symptoms at work and dissatisfaction with the air quality at work. The results are intended to help support evidence-based, energy efficient, but health-protective ventilation standards for commercial buildings.

Standards for minimum VRs in commercial buildings historically have been based on laboratory studies of acceptability of air quality that considered occupants to be the only pollutant sources. More recently, standards have considered, to a limited extent, research on how VRs affect prevalence of "sick building syndrome" (SBS) symptoms. Research now suggests that current ventilation standards provide neither adequate protection from SBS symptoms nor satisfactory perceived air quality in offices [1-5].

Pollutants in office buildings, which may cause adverse effects in occupants, can be emitted by the buildings and everything within, including furniture, equipment, and occupants themselves. Outdoor air brought into offices by mechanical ventilation systems is the primary means by which levels of indoor-generated pollutants are reduced. Heating or cooling this outdoor air to comfortable indoor levels requires increased energy as VRs increase. In setting energy-conscious VR standards, adverse effects on occupants from inadequate ventilation can be considered as costs to be weighed against the benefits of reduced energy use and energy costs. The human outcomes of potential concern in setting commercial VR standards (although not all are considered currently) include building-related symptoms, infectious respiratory disease, asthma exacerbations, illness-related work absence, reduced work performance, and poor perceived air quality.

Building occupants can emit infectious respiratory agents that cause illness in other occupants [6]. The hypothesis underlying this study is that sufficiently lower VRs in office buildings, indicated by higher measured carbon dioxide (CO_2) concentrations, would lead to greater indoor air concentrations of agents causing infectious respiratory disease, which would lead to higher rates of illness absence in the occupants. This hypothesis is supported by a finding in a prior study [7] of a 35% reduction in short-term illness absence among office workers with VRs of 24 L/s per person compared to those with 12 L/s per person, based on VRs estimated from CO_2 data. Milton et al. [7] presumed that short-term illness absence was primarily from respiratory infections. Other prior findings [6] also provide support for the hypothesis. There are currently few published data in the archival literature documenting associations between ventilation rate and illness absence in office environments.

Chemical and non-infectious biological pollutants indoors may also cause irritation, allergies, or dissatisfaction with indoor air quality. SBS symptoms have been used extensively as a measure of health-related outcomes in offices. Lower VRs have been associated with elevated prevalence and intensity of SBS symptoms [1, 8]. It is not known if these symptoms are severe enough to contribute to illness-related absence. SBS symptoms also could be considered as costs, to be weighed against energy benefits of lower VRs.

This study estimates VRs from measured indoor CO_2 concentrations, collected and logged in real time continuously for one year, minus estimated outdoor concentration. Also, since CO_2 is a product of human respiration, the indoor CO_2 concentration itself can be considered as a proxy, in evaluating effectiveness of ventilation for controlling airborne concentrations of human-produced infectious respiratory agents that contribute to absence. The study analyses estimate the associations of both VRs and CO_2 concentrations with occupant outcomes, including respiratory infections, illness absence, symptom severity, and perceived air quality. This information on human health effects will provide input into decisions about costs and benefits of decreasing or increasing minimum VR standards.

Many buildings have economizer control systems that increase VRs above a set minimum value, by increasing outdoor air flow rates during times of cool to moderate outdoor air temperatures, and reducing building energy consumption for air-conditioning. In general, minimum VRs are provided when the outdoor temperature is either above the desired indoor temperature or below approximately 10^{o} C; however, control strategies vary somewhat from building to building. In much of California, economizers increase VRs above the minimum VR most of the time. Dutton and Fisk [9] estimated that overall, for California offices with economizers, VRs will exceed the set minimum VR approximately 80% of the time.

Methods

Building recruitment

Buildings in California were solicited for participation by emails, flyers, and phone calls to the employers. Eligible office buildings were from the public or private sector in three distinct climatic regions of California – Bay Area, Central Valley, and South Coast. In each selected building, a study space with at least 30 occupants was selected, either a subset of the building and its workers or the full building, within which relatively uniform VRs were anticipated (e.g., contiguous space, space with air recirculation by air handling systems). A single building could contain multiple separate study spaces. Buildings or study spaces containing unusual contaminant sources were excluded. The target size of the study was a total of 30-40 study spaces, including 50 or more workers in each.

Given the high expected refusal rate during building recruitment (based on our prior experience), the sample was not intended to be representative of California commercial buildings, but a sample of convenience using available opportunities. Recruitment, enrollment, and data collection were conducted in a rolling manner, so that data collection began in the earliest recruited buildings while other buildings were still being recruited. Data were collected for at least a full year within each building, but study periods were not simultaneous across all study buildings.

Environmental Data

Several types of environmental data were collected: measurements of indoor CO_2, temperature (T), and relative humidity (RH), along with selected characteristics of the buildings and ventilation systems. Other indoor air pollutants were not measured. CO_2 was monitored by Vaisala CARBOCAP™ #GMW110 sensors (Vaisala Inc., Boulder CO). HOBO T & RH loggers

(Onset Computer Corporation, Cape Code, MA) were used to measure T and RH and to log the CO_2 data.

CO_2, T, and RH were measured at continuous 10-minute intervals at 2-3 indoor locations per study area. In an initial visit at each building, the sensor packages (CO_2 sensor plus T and RH data loggers) were installed at suitable locations away from likely direct occupant exhalation, e.g. attached to the top of space partitions and in common areas such as hallways. A contact at each building was queried about which 2-hour period in the morning in each study space was most likely to have a stable number of occupants. Each quarter-year, in-place sensor packages were replaced with sensor packages containing newly-calibrated CO_2 sensors. Sequential waves of replacement were used within the study buildings. Seventy sensor packages were used in the study, 66 more than once.

Data from the two to three sensors within each study space were first averaged at each time point to provide overall real-time estimates for the study space. As the primary VR metric for analysis (VR Method 1), real-time spatially averaged CO_2 data from 8 a.m. to 5:30 p.m. on workdays were used to estimate daily workday VRs (as outdoor airflow rates in L/s per person) using the equilibrium CO_2 method; i.e., from observed peak moving 60-minute-averaged CO_2 concentrations, per ASTM D6245-12 [10]. These calculations assumed that daily VRs in each office were stable, CO_2 reached equilibrium daily in each. The outdoor air flow Q (m^3/h) was estimated from the maximum indoor CO_2 concentration as follows:

$$\frac{Q}{N} = \frac{S}{\left(C_{\max} - C_o\right)} ' \frac{\text{h}}{3600\ \text{s}} \qquad (1)$$

where Q/N (L/s-person) is the per-person outdoor airflow rate, C_o (g/m^3) is the outdoor CO_2 concentration (set to 380 ppm here), C_{max} (g/m^3) is the maximum hourly averaged CO_2 concentration measured indoors between 8:00 a.m. and 5:30 p.m., and S is the CO_2 generation rate, set at 18.6 L/h-person (Mudarri, 1997) for sedentary persons with an activity level of 1.2 met units.

The underlying assumptions of equation one were often violated, leading to inaccurate VRs. An alternative method (VR Method 2) was also used for estimating VRs, based on the build-up of indoor CO_2, required no assumption about equilibrium but assumed stable ventilation rates and occupancy during selected periods. This method considers build-up of CO_2 during selected 2-hour periods in each study space with relatively stable occupancy numbers, and also in the afternoon after workers returned from lunch. Additional information about the CO_2 measurements and about both VR estimation methods is available in Additional file 1.

These two estimators of daily VR were intended for use in two ways: to calculate prior 3-month averages of daily VRs, for analyses with the occupant outcomes involving occupant recall over the prior 3 months (respiratory infections and illness absences); and as daily values, for analyses with the occupant outcomes linked to the day of the occupant survey (symptoms and perceived air quality). Metrics of both daily time-averaged mean CO_2 and daily peak 60-minute-averaged

CO_2 concentrations were also used in analyses without conversion to VR estimates, as both 3-month-average and daily values.

The particle filtration in the heating, ventilating, and air-conditioning (HVAC) systems in the study buildings were characterized via interviews with building managers and data obtained from filter manufacturers. Use of economizer cycles in the HVAC was determined by interviews with building managers.

Human outcomes data
Initial development of tools and procedures for data collection from occupants included a human subjects consent form, a web-based survey tool developed for administration via the Internet (based on revision of a previously used survey), and data handling protocols to ensure the confidentiality of personal information. Before collecting human subjects data, a human subjects protocol was approved by the Lawrence Berkeley National Laboratory Human Subjects Committee.

Data on occupants and their outcomes were obtained from occupant surveys every three months during the study, starting three months after initial sensor installation in the building, using the web-based survey tool. See Table 1 for a schedule of sensor installation and survey administration. In the initial survey for each participant only, data were obtained on personal/demographic variables that can influence risk of respiratory illness (age, gender, smoking status, asthma status), home variables (young children at home), and work factors (job type, office space sharing, hours worked in building). See Additional file 2 for questions in the initial and recurring surveys.

In the initial and in each recurring survey, data were obtained on the number of episodes of infectious respiratory illnesses and the number of days of absence caused by respiratory illnesses, in the prior three months. These surveys also included questions on perceived air quality and on severity of four symptoms on the day of the survey. Respondents were asked to rate the indoor air quality in two questions, on acceptability of air quality and acceptability of odor, with the response scale for each ranging from 1 to 7 (“clearly acceptable” to “clearly unacceptable”). The

Table 1. Schedule for sensor installation and survey administration in each building during the year of study

Months	1	2	3	4	5	6	7	8	9	10	11	12	13
Period for ventilation rate averaging		1			2			3			4		
Sensor Installation*	●			●			●			●			
Survey Administration				#1			#2			#3			#4

* in period 1, initial installation of calibrated sensors; in later periods, replacement by newly calibrated sensors

symptom questions included: dry, itching, or irritated eyes; headaches; unusual tiredness or fatigue; and congested nose, asking respondent to rate the symptom at that time on a severity scale from 0-10 (none to very severe) and also, if they reported that symptom at a level of 1 or higher, whether they had the symptom before arriving at work that day.

To improve survey response rate, a small financial incentive was provided automatically when each survey was completed: upon submission of each survey, a $4 gift certificate was provided in an email as a numeric code for online redemption, except that for the fourth survey among those also completing the prior three surveys, an $8 incentive was provided. In several buildings, financial incentives were not allowed. In one of these buildings, however, the facility manager instituted a competition between the two study spaces there on their survey response rate throughout the study. The building managers received no information on responses of individuals.

Analysis

Collected survey data were omitted from occupants who reported working less than 20 hours per week in their building and from those who failed to complete an initial questionnaire with background information.

Environmental data, collected in real time during the study period, were excluded from analyses outside the weekday hours of 8:00 a.m. – 5:30 p.m., on U.S. federal holidays, and during periods of local shutdown at university buildings. Also, any day in a study space with no apparent elevation of indoor CO_2 above approximately 400 ppm was excluded as a non-work day in that space.

Data collected were analyzed to assess relationships between estimated ventilation rates or CO_2 concentrations, either daily or averaged over the prior 3-month periods, and occupant outcomes assessed in the survey at the end of each quarter (Table 1). Data analyses were performed using Stata v. 11 (StataCorp LP, College Station, TX, USA; www.stata.com). Analyses of the longitudinal data were at the individual (subject) level, and included unadjusted and adjusted models accounting for repeated measurements on individuals.

Analyses provided point estimates and confidence intervals for the estimated relationships between variables. Appropriate statistical models were selected for analysis of each type of human outcome, all using “bootstrap” procedures for variance of estimates to account for clustering on individuals and study spaces. For respiratory illness episodes and illness absence days, zero inflated negative binomial, zero inflated Poisson, negative binomial, or Poisson models were used, which produce point estimates of incident rate ratios (IRRs). (Details of how these models were chosen are provided in Additional file 3.) For symptom outcomes, which have highly skewed distributions with many zero values, zero-inflated negative binomial models were used. For perceived air quality and odors, generalized estimating equation (GEE) linear and logistic regression models were used, which produce point estimates of regression coefficients and of odds ratios (ORs), respectively.

All adjusted models included covariates for potential confounding as appropriate. For repeated measures analyses within individual subjects and study spaces, adjustment for unchanging personal variables as potential confounding was not necessary. For analyses of respiratory illness episodes and related absences, a covariate was included in models for a "respiratory illness season." (Plots of prior respiratory illness by month showed higher numbers reported on surveys in the months of January through April for illness in the prior three months, corresponding to a season of increased respiratory illness spanning October-April; this was used to define the respiratory illness season.) Models for each symptom severity outcome on the day of the survey included a covariate indicating whether the respondent already had that specific symptom when arriving at work. The models used, along with the specific types of exposure variables (e.g., estimated ventilation rate or CO_2 concentrations) and the covariates included in models, are described in Additional file 3.

Results

Building recruitment was challenging: only a small proportion of contacted buildings agreed to participate. A total of 17 separate study areas within 10 office buildings were successfully recruited for participation. Due to loss of environmental data, 16 study spaces in nine buildings were included in analyses (Table 2). Two included spaces contained fewer than 50 office workers. All the included buildings but two (engineering firms) were in the public sector (state or municipal government, higher education, research). All study spaces had air-conditioning and were reported to have economizers. Data collection from sensors in the first participating building began in May 2012, and the first occupant survey was conducted in that building 3 months later, in August 2012. (Data collection was continuous except in study spaces 2a and 2b, where a major furniture move after the third period required a 3-month suspension of the study before proceeding with the final 3-month period.) Completed data collection from sensors and surveys was concluded in all study spaces by October, 2013, except in space 9, which was enrolled so late that data from the fourth survey was not available in time for analysis deadlines .

Table 2. Buildings participating in the HZEB Office Building Ventilation Rate Study

Study Space	**Sector**	**Study Area**	**Study Area Size (m^2)**	**No. of Occu pants**	**Density of Occu-pancy (/10^2 m^2)**	**Date Initial Sensors Installed**	**End Date of 4th survey**	**Particulate Filter Efficiency (MERV)**
Bay Area								
1a	Public	Fl 2 (north)	920	53	5.7	2/29/2012	6/14/2013	8
1b	Public	Fl 2 (south)	830	41	4.9	2/29/2012	6/14/2013	8
2a	Private	Fl 6	2,310	140	6.1	3/15/2012	11/1/2013	14
2b	Private	Fl 7	2,310	127	5.5	3/15/2012	11/1/2013	14
3a	Public	Fl 7	1,860	71	3.8	4/18/2012	8/6/2013	14
3b	Public	Fl 12	1,860	68	3.7	4/18/2012	8/6/2013	14

3c	Public	Fl 13	1,860	100	5.4	4/18/2012	8/6/2013	14
3d	Public	Fl 15	1,860	33	1.8	4/18/2012	8/6/2013	14
6	Public	Fl 2 + part 3	1,370	64	4.7	5/24/2012	6/14/2013	8
Central Valley								
4	Public	Fl 3 (part)	1,070	74	6.9	5/3/2012	6/14/2013	8
9	Public	Fl 2+3 (1wing)	1,370	21	1.5	12/12/2012	8/30/13*	8
South Coast								
5a	Private	Fl 1	1,440	61	4.2	5/15/2012	6/14/2013	8
5b	Private	Fl 2	1,630	115	7.1	5/15/2012	6/14/2013	8
7	Public	Fl 1, 2, 3, 4	4,170	86	2.1	10/03/2012	11/1/2013	8
8b	Public	Fl 1	2,240	114	5.1	10/3/2012	11/1/2013	8
8c	Public	Fl 3 (part)	2,240	50	2.2	10/3/2012	11/1/2013	8

* end date of 3rd survey, 4th survey not included in this space
Abbreviations: MERV, Minimum Efficiency Reporting Value; N, number; occs, occupants.

Occupant data

Response rates to the occupant survey were lower than expected, despite use of financial incentives (Additional file 4).: the 1,297 valid surveys received represented an overall 27% response on the four surveys, varying from 16 to 41% across study spaces. Response rates for individual surveys in each study space ranged from 8 to 54%. However, the incentives, of about $4-$8 for each 5-minute survey, did increase response over the non-incentive study spaces by 50% (from 18% to 27%). The competition set up between two non-incentive study spaces within one building (1a and 1b), with no prize other than pride in winning, produced a response rate 78% higher than other regular non-incentive spaces, and even 18% higher than the spaces with financial incentives.

Table 3 provides information on the study respondents. No data were available to allow comparison of survey participants to nonparticipants. Respondents included slightly more males (53%), included a broad range of ages from under 30 (17%) to over 50 (29%), and were highly educated (98% with at least a college degree, 45% with a graduate degree). Most (81%) had no children up to age 3 years at home. Most (78%) reported never smoking. Half (50%) reported some history of allergy or asthma, including 25% for hay fever and 16% for asthma, and 11% reported current asthma. Most participants (75%) worked in open office spaces; 70% shared their workspace with at least 7 others, with only 18% in private offices. Over half (54%) reported working over 40 hours per week. Most (68%) reported high levels of job stress, but only 26% reported high levels of job dissatisfaction.

Table 3. Characteristics of survey respondents*

	n (%)***	Categories used in adjusted models
Hours worked each week in building:**		
21-40	182 (46%)	21-40
>40	216 (54%)	>40
Number of others sharing workspace:**		
0	73 (18%)	0
1-2	25 (6%)	1 or more
3-6	19 (5%)	
7 or more	279 (70%)	
Job stress (1=not at all, 7=extremely):**		
1-2	17 (4%)	(not included)
3-4	110 (28%)	
5-7	270 (68%)	
Job dissatisfaction (1=very satisfied, 7=very dissatisfied):**		
1-2	152 (39%)	1-2
3-4	133 (34%)	3-4
5-7	102 (26%)	5-7
Number of children up to age 3 years at home:		
0	321 (81%)	0
1-2	68 (17%)	1 or more
3 or more	7 (2%)	
Smoking status:		
Never	302 (78%)	Never
Former	66 (17%)	Former/current
Current	17 (4%)	
Age		
Under 30	67 (17%)	Under 30
30-39	113 (29%)	30 or over
40-49	99 (25%)	
50 or over	113 (29%)	
Gender		
Female	185 (47%)	Female
Male	208 (53%)	Male
Education completed		
High school	9 (2%)	
College degree	210 (53%)	No graduate degree
Graduate degree	176 (45%)	Graduate degree
Prior medical diagnoses:**		
Asthma	62 (16%)	
Current asthma	45 (11%)	
Eczema	43 (11%)	
Hay fever (pollen allergy)	100 (25%)	
Dust allergy	84 (21%)	
Mold allergy	53 (13%)	
Any prior allergy	183 (46%)	Any prior allergy
No prior allergy	201 (50%)	No prior allergy

* after exclusion of surveys from workers who worked <21 hours/week in the building and from those not completing an initial survey with background data
** from initial survey response to a question repeated on each survey
*** proportions are calculated using total of non-missing answers

Table 4 shows the distributions, in each study space and overall, for the number of respiratory infection episodes reported in the prior three months and for respiratory illness-related absences in the prior three months. For the number of respiratory infection episodes in the prior 3 months, the overall mean was 0.92, with a range across study spaces from 0.67 to 1.32. The 95th percentile value overall was 3, ranging in specific study spaces from 2 to 4. For the number of respiratory illness-related work absences in the prior 3 months, the overall mean was 0.78, with a range across study spaces from 0.10 to 1.38. The 95th percentile value overall was 4, ranging in specific study spaces from 1 to 6.

Table 4. Respiratory illness outcomes among respondents*

Study Space	**Number of respiratory infection episodes in prior 3 months**				**Number of days of respiratory illness-related work absences in prior 3 months**			
		percentiles				percentiles		
	mean	50%	75%	95%	mean	50%	75%	95%
Bay Area								
1a	0.71	0	1	3	0.57	0	1	4
1b	0.85	1	1	3	0.37	0	0	1
2a	0.92	1	1	3	0.67	0	1	3
2b	0.98	1	2	3	0.80	0	1	3
3a	0.94	1	1	4	1.34	0	2	6
3b	1.32	1	2	4	1.38	1	2	5
3c	1.00	1	2	3	1.17	.5	2	4
3d	0.70	0	1	2	0.70	0	1	4
6	0.92	1	1	2.5	0.65	0	1	4.5
Central Valley								
4	0.71	1	1	2	0.61	0	1	3
9	1.10	1	2	3	0.10	0	0	1
South Coast								
5a	0.94	1	1	3	0.42	0	0	3
5b	1.01	1	1	3	0.49	0	1	2
7	0.91	1	2	3	0.96	0	2	4
8b	0.67	1	1	2	0.60	0	0	4
8c	*1.00*	1	1	4	0.90	0	2	4
TOTAL	0.93	1	1	3	0.78	0	1	4

* after all exclusions (see Table 3 footnote)

Table 5 describes symptoms reported on the days of the surveys, in each space and overall, including all eligible surveys. The overall proportions of respondents reporting any of eye, headache, fatigue, or nose symptoms at work (considering all eligible surveys from all study spaces together) were 65%, 35%, 61%, and 51% respectively, with respective mean severity scores among those reporting any of each symptom of 4.4, 3.8, 4.4, and 4.0 out of 10. For the eye, headache, fatigue, and nose symptoms, the minimum proportions reported in any study space were 40%, 15%, 44%, and 30%, and the maximum proportions reported were 82%, 57%, 74%, and 68%, respectively (excluding study space 9, which had few total responses). Among those reporting any symptom responses for eye, headache, fatigue, and nose symptoms, the ranges across study spaces of symptom severity scores were 3.0-5.4, 2.3-5.1, 3.6-6.2, and 3.1-4.8. Additional file 5 shows the number and proportion of occupants in each building with prior experience of each type of symptom on the day of the survey. Prior symptoms (before work on the survey day) were common: overall proportions of surveys reporting prior eye, headache, fatigues, and nose symptoms were 38%, 31%, 56%, and 65%, respectively

Table 5. Symptom* outcomes among respondents on day of survey**

Study Space	Occupants reporting any (nonzero) symptom at work				Mean severity among those reporting any symptom			
	n (%)							
	eye	head	fatigue	nose	eye	head	fatigue	nose
Bay Area								
1a	48 (64%)	23 (31%)	42 (56%)	32 (43%)	4.77	4.30	4.24	3.56
1b	23 (50%)	12 (27%)	26 (57%)	24 (52%)	4.26	2.50	3.62	3.46
2a	99 (58%)	53 (31%)	97 (57%)	83 (49%)	4.40	3.60	4.14	3.83
2b	82 (63%)	30 (23%)	83 (64%)	64 (49%)	3.72	4.00	4.28	3.36
3a	71 (75%)	39 (41%)	64 (68%)	65 (68%)	4.10	4.05	4.45	4.31
3b	47 (71%)	34 (52%)	40 (61%)	43 (65%)	5.43	5.09	6.15	4.74
3c	100 (82%)	70 (57%)	91 (74%)	77 (63%)	5.25	4.61	4.88	4.30
3d	44 (81%)	22 (41%)	31 (57%)	31 (57%)	2.95	3.59	3.77	4.45
6	16 (40%)	6 (15%)	18 (45%)	20 (50%)	3.50	4.00	4.22	3.10
Central Valley								
4	32 (54%)	25 (42%)	32 (54%)	22 (37%)	4.56	2.72	3.75	3.64
9	9 (90%)	3 (30%)	7 (70%)	9 (90%)	4.44	2.33	4.14	4.00

South Coast								
5a	38 (49%)	15 (19%)	42 (55%)	23 (30%)	3.97	3.13	3.57	4.04
5b	91 (65%)	52 (37%)	96 (70%)	71 (51%)	4.05	2.94	4.32	3.82
7	32 (59%)	20 (37%)	33 (61%)	23 (43%)	4.72	3.85	4.88	4.83
8b	38 (69%)	15 (27%)	24 (44%)	20 (36%)	4.13	3.52	3.83	4.30
8c	45 (79%)	23 (40%)	39 (68%)	26 (46%)	5.40	3.61	5.38	5.00
TOTAL	815 (65%)	442 (35%)	765 (61%)	633 (51%)	4.40	3.81	4.41	4.03

* symptoms are: dry, itching, or irritated eyes; headaches; unusual tiredness or fatigue; and congested nose; response scale ranges from 0 (none) to 10 (very severe)
** after all exclusions (see Table 3 footnote); includes data from respondents eligible for survey and who also answered both parts of the symptom question

Table 6 describes the reported acceptability of indoor air quality and odors, by space and overall, including all eligible surveys. The proportion of surveys rating the indoor air quality as unacceptable (on a dichotomous scale) was 10.2% overall, ranging across study spaces from 2.5 to 30%. Averaged over the 4 surveys in each space, only two of 16 spaces (8c and 9) failed to provide acceptable air quality for at least the minimum 80% proportion of occupants assumed in the American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE) 62.1 ventilation standard. The overall mean IAQ acceptability score for all surveys was 4.6 (on a continuous scale, with 1=barely acceptable and 10=completely acceptable), ranging across study spaces from 3.0 to 6.1. The proportion of surveys rating the odors as unacceptable was 3.7% overall, ranging across study spaces from 0 to 11%. The overall mean odor acceptability score for all surveys was 5.5, ranging across study spaces from 4.1 to 6.3.

Environmental data –
Based on recalibration of CO_2 sensors after deployment in the field for 3-month periods, sensor drift was small, approximately ±5% (see Additional file 1). Temperature sensors were determined to have read fairly consistently 1 ºC high, due to an internal heat source in monitoring modules and temperature values used in modeling were adjusted accordingly.

Table 7 summarizes, by study space and specific survey periods for each, median values for the prior three months of three VR-related variables: daily VRs (Method 1), daily mean CO_2, and daily maximum CO_2. Quarterly (per three-month) median VRs in study spaces ranged from 6.9 to 65.8 L/s per person, medians of daily mean CO_2 from 425-957 ppm, and medians of daily maximum CO_2 from 494-1230 ppm. VRs were uniformly high relative to the current minimum VR standards for office space: 8.5 L/s (17 cfm) per person from ASHRAE 62.1, at the default density of occupancy, and 7 L/s (15 cfm) per person from California Title 24. Other than one median quarterly VR of 6.9 L/s-person in space 4, all other quarterly medians exceeded 13 L/s per person, or almost double the California

Table 6. Environmental acceptability outcomes

Study Space	Acceptability of indoor air quality		Acceptability of odors	
	Percent rating as unacceptable	Overall mean IAQ acceptability score	Percent rating as unacceptable	Overall mean odor acceptability score
Bay Area				
1a	6.8%	5.3	2.7%	5.9
1b	4.4%	5.4	0.0%	6.0
2a	7.0%	4.8	3.6%	5.5
2b	6.9%	5.0	3.9%	5.7
3a	13.8%	4.4	2.1%	5.9
3b	11.1%	4.2	6.3%	5.3
3c	19.2%	3.3	11.0%	4.2
3d	11.1%	5.0	0.0%	6.1
6	2.5%	6.1	2.5%	6.2
Central Valley				
4	10.3%	3.8	1.8%	5.2
9	30.0%	3	3.7%	4.1
South Coast				
5a	10.3%	5.1	1.3%	6.3
5b	8.9%	4.5	0.7%	5.8
7	3.8%	5.5	1.9%	5.8
8b	5.7%	4.9	7.4%	4.7
8c	22.8%	3.3	5.3%	5.4
Overall	10.2	4.6	3.7	5.5

standard. Figure 1 shows distributions of daily maximum CO_2 measurements, over the entire study, by study space. Figure 1 shows that the study spaces had generally low maximum CO_2 concentrations and thus high VRs, except space 4, which had a slightly higher CO_2 distribution. Relative CO_2 levels across buildings were similar for maximum and mean CO_2. Distributions of daily mean CO_2 values are provided in Additional file 6. Figure 2 shows daily maximum CO_2 values over time in each study space. Most study spaces had relatively uniform maximum CO_2 throughout the study, with the exception of space 7 and, to a lesser extent, 8b. Patterns for maximum and mean daily CO_2 over time were similar. Space 4, Survey 3, had the most low VRs and high CO_2 levels; otherwise the ranges across buildings and surveys were narrower. Distributions of daily mean values over time are provided in Additional file 7.

Additional file 8 shows the distributions of VRs in each study space estimated using VR Method 1, i.e., calculated with equation 1, plus the 5th percentile values as indicators of minimum VRs. Minimum VRs based on the 2.5th percentile were similar. The estimated minimum VRs

Table 7. Prior three-month* median of daily ventilation rates (VRs)**, daily mean CO_2, and daily maximum CO_2, by study space

Study Space	Three-Month Median of Daily VRs: (L/s-person)				Three-Month Median of Daily Mean CO2: (ppm)				Three-Month Median of Daily Maximum CO2: (ppm)			
	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4
Bay Area												
1a	21.2	19.2	19.7	20.9	571	605	607	58	669	703	702	679
1b	18.8	17.1	17.1	17.6	573	603	603	579	723	731	749	729
2a	21.3	17.9	13.9	19.6	569	615	660	587	661	713	803	678
2b	21.5	18.4	13.8	22.0	570	602	657	566	660	699	803	660
3a	17.8	25.2	22.1	19.8	550	534	513	533	713	628	664	672
3b	38.9	36.4	31.3	39.4	470	482	481	463	538	547	578	541
3c	13.7	24.4	19.6	15.4	587	532	526	534	873	652	704	843
3d	29.8	34.9	31.9	28.6	480	496	475	483	588	571	566	602
6	65.8	41.9	32.6	38.2	432	471	492	477	500	547	580	567
Central Valley												
4	18.8	13.1	6.9	14.0	602	663	957	656	720	825	1230	822
9	20.7	25.6	20.3	NA	563	529	577	NA	733	699	703	NA
South Coast												
5a	15.4	17.5	16.0	15.8	646	605	647	653	759	732	777	764
5b	17.6	20.1	17.2	20.9	555	572	580	569	711	682	752	673
7	23.1	28.4	27.0	27.1	574	530	538	541	659	594	618	629
8b	27.9	23.4	58.1	52.6	512	507	446	441	726	835	568	584
8c	30.8	41.6	58.8	64.9	525	471	448	425	581	528	501	494

* prior three-month period ending on the first day of each survey period in each space
** VR Method 1

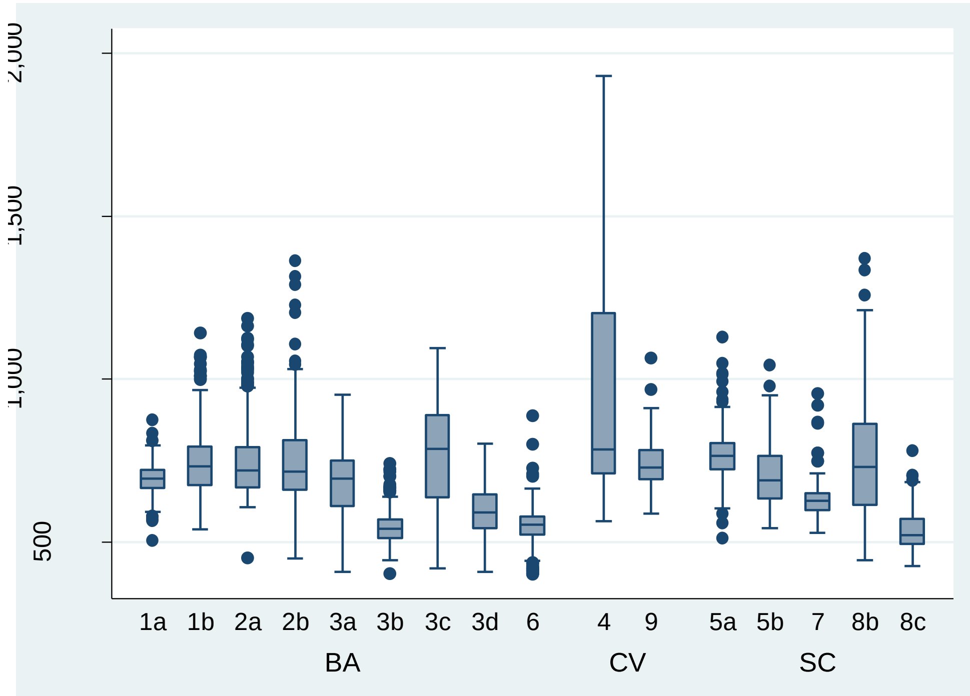


Figure 1. Distributions of daily maximum indoor CO_2 measurements, by study space grouped by climate zone (boxes show median, 25th and 75th percentiles; whiskers, 75th percentile plus 1.5 times the interquartile distance, and 25th percentile minus 1.5 times the interquartile distance)

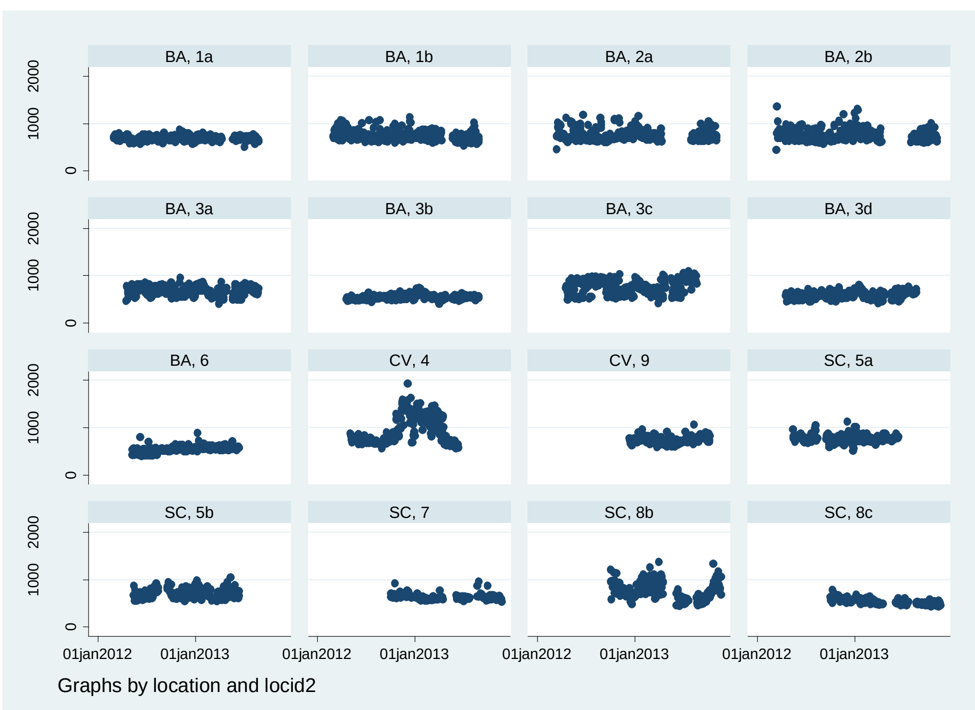


Figure 2. Daily CO_2 maximum indoor values over time (y-axis, in ppm, per study space grouped by climate zone

substantially exceeded the 7 L s^{-1} per person requirement in most study spaces, with an average estimated minimum of 15 L/s per person. In 13 of 16 study spaces, the estimated minimum VR exceeded 10 L/s per person.

Because the estimated daily VR metric was extremely variable, analyses used 3-month VR averages. Measured CO_2 metrics but not estimated daily VRs were used in analyses of same-day symptoms or acceptability of air. Because economizer systems were present in all study spaces it was not possible to include economizer presence in models. The efficiency of particle filters, expressed as a Minimum Efficiency Reporting Value (MERV) rating ranging from 1-16, was clustered at two values, 8 and 14 MERV, with the higher efficiency present in the study spaces in only two buildings, so it was also not possible to include this in models.

Environment and outcome results

Additional file 9 provides summaries of occupant outcomes by categories of various demographic and personal variables of occupants. Workers in private offices had the lowest proportions of respiratory infections and days of respiratory illness-related work absence, and the highest scores for acceptability of indoor air quality (IAQ) and odors, but these outcomes did not worsen consistently as the number of others sharing the workspace increased. Sharing workspace with fewer others also did not show consistent associations with fewer symptoms. Very low job stress and low job dissatisfaction were associated with unusually low levels of respiratory illness-related absence, relatively high acceptability of IAQ and odors, and somewhat lower proportions reporting most symptoms. Smokers reported relatively low levels of respiratory illness episodes and related work absence, relatively low levels of most symptoms, and higher levels of environmental acceptability. Females reported many more respiratory illness-related work absences, more of most symptoms, and somewhat lower environmental acceptability.

Table 8 summarizes the associations, unadjusted and adjusted, between CO_2 and VRs in the prior three months and the two respiratory illness outcomes, estimated from zero-inflated negative binomial models. Covariates and their categories used in these adjusted models are described in Table 3. None of the unadjusted or adjusted estimates were significantly associated with CO_2 or VR metrics. All estimates not equal to 1.0 were in directions opposite those hypothesized (below rather than above 1.0 for the CO_2 metrics, and above rather than below 1.0 for VR). For analyses using the alternative VR metric based on curve-fitting for CO_2 increases, results were similar, except that for respiratory illness-related absences, with increased VR there was a small statistically significant increase in estimated illness absence– OR (95% CI) 1.015 (1.0005-1.03), p=0.043 – but not in respiratory illness episodes – 1.001 (0.90-1.008), p=0.78.

Additional file 10 summarizes associations between the same variables but estimated from logistic regression models. All the unadjusted estimates were in the hypothesized directions, and all the adjusted estimates in directions opposite those hypothesized, although none were statistically significant. The directions of all adjusted estimates, and the magnitudes for the respiratory illness episodes, were similar to (or showed smaller effects) those from the zero-inflated negative binomial models.

Of the four other covariates in models for the two respiratory illness-related outcomes, only respiratory illness season had strong and consistent associations, with highly significant IRRs of about 1.5 and, from logistic regression models, ORs of 2.0 for both illness episodes and days of illness absence. Shared workspace had highly significant positive associations only in the logistic models, with ORs of 1.6 for illness episodes and 2.0 for days of illness absence. Young children at home had significantly elevated associations only in logistic models for illness episodes, with ORs of 1.7. Ever smoking had no consistent associations with either outcome.

Table 8. Unadjusted and adjusted associations, as incident rate ratios (IRRs) and 95% CIs,* between CO_2 and ventilation rates in the prior three months, and respiratory illness outcomes, estimated from zero inflated negative binomial (or, as noted, negative binomial or zero-inflated Poisson) models

	Number of respiratory infection episodes in prior 3 months				Number of days of respiratory illness-related work absences in prior 3 months			
	unadjusted		adjusted##		unadjusted		adjusted##	
	IRR	(95% CI)	IRR	(95% CI)	IRR	(95% CI)	IRR	(95% CI)
Median of daily CO_2 mean, prior 3 months	0.98^	(0.87, 1.10)	0.93#	(0.83, 1.05)	0.87	(0.74, 1.03)	0.86	(0.69, 1.07)
Median of daily CO_2 maximum, prior 3 months	0.98^	(0.91, 1.06)	0.94#	(0.86, 1.02)	0.97	(0.88, 1.08)	0.97	(0.84, 1.12)
Median of daily estimated VR, prior 3 months	1.00^	(0.996, 1.02)	1.00#	(0.99, 1.02)	1.01	(0.997, 1.02)	1.01	(0.99, 1.03)

* The IRR is interpreted as the multiplicative change in estimated rate of outcomes for each increase of 100 ppm CO_2 or 1 L/s per person of VR. Estimates for VR models were hypothesized to be in the opposite direction as CO_2 models.

^ Negative binomial model

Zero-inflated Poisson model

Models adjusted for: smoking, young children in home, people sharing workspace, respiratory illness season (illness reporting period in October—April); see Table 5.

Table 9 summarizes the associations between same-day CO_2 metrics and symptoms (as continuous outcomes), estimated from zero-inflated negative binomial models. None of the adjusted estimates were statistically significant, and most were small (changes of 1% or less) and in the direction opposite that hypothesized. Table 10 summarizes the associations between the same-day CO_2 metrics and acceptability of indoor air and odor (as dichotomous outcomes), estimated from logistic regression models. (The ORs in this table are for the IAQ or odor being

Table 9. Unadjusted and adjusted# associations between same day CO_2 and symptoms (as continuous outcomes), estimated as incidence rate ratios (IRRs) from zero inflated negative binomial models

	Symptoms															
	eyes				Headache				Fatigue				Nose			
	unadjusted		adjusted#		unadjusted#		adjusted#		unadjusted		adjusted#		unadjusted		adjusted#	
	IRR	(95% CI)	IRR	(95% CI)	IRR	(95% CI)	IRR	(95% CI)	IRR	(95% CI)	IRR	(95% CI)	IRR	(95% CI)	IRR	(95% CI)
Mean CO_2 on day of survey (per 100 ppm)	0.99	(0.95, 1.03)	0.98	(0.94, 1.03)	0.98	(0.92, 1.04)	0.99	(0.92, 1.07)	0.96	(0.91, 1.01)	0.99	(0.94, 1.04)	0.98	(0.92, 1.03)	1.00	(0.95, 1.05)
Maximum CO_2 on day of survey (per 100 ppm)	1.00	(0.97, 1.03)	1.00	(0.97, 1.03)	0.99	(0.95, 1.04)	1.00	(0.95, 1.05)	0.98	(0.94, 1.01)	0.99	(0.96, 1.03)	1.00	(0.96, 1.04)	1.01	(0.97, 1.05)

Models adjusted for job dissatisfaction, age, gender, education, smoking, shared workspace, any allergic history, and current asthma (see Table 5 for covariates) and also prior symptom before work and mean indoor temperature on day of survey.

Table 10. Unadjusted and adjusted# associations, estimated as odds ratios (ORs), between same-day CO_2 and acceptability of indoor air (as dichotomous outcomes), estimated from logistic regression models

	Acceptability of indoor air quality, dichotomous				Acceptability of odors, dichotomous			
	unadjusted		adjusted#		unadjusted		adjusted#	
	OR	(95% CI)	OR	(95% CI)	OR	(95% CI)	OR	(95% CI)
Mean CO_2 on day of survey (per 100 ppm)	1.00	(0.83, 1.22)	1.02	(0.95, 1.24)	1.11	(0.83, 1.49)	1.17	(0.88, 1.56)
Maximum CO_2 on day of survey (per 100 ppm)	0.98	(0.88, 1.09)	0.99	(0.88, 1.11)	1.02	(0.87, 1.20)	1.05	(0.90, 1.23)

Models adjusted for job dissatisfaction, age, gender, smoking, and shared workspace (see Table 5 for covariates) and also mean indoor temperature on day of survey.

judged acceptable vs. unacceptable.) None of the adjusted estimates were statistically significant, and directions were mixed.

Table 11 summarizes the associations between the same-day CO_2 metrics and acceptability of indoor air and odor (as continuous outcomes), estimated from linear regression models. (The coefficients in this table are for the additive change in acceptability score for IAQ or for odor, on a scale of 1-7, with positive coefficients indicating improved acceptability.) None of the adjusted estimates were significant, and magnitudes were mixed. Female gender and greater job dissatisfaction were associated with less acceptability of IAQ.

Table 11. Unadjusted and adjusted# associations between same-day CO_2 and acceptability of indoor air (as continuous outcomes), estimated from linear regression models

	Acceptability of indoor air quality, continuous				Acceptability of odors, continuous			
	unadjusted		adjusted#		unadjusted		adjusted#	
	Coeffi-cient	(95% CI)	Coeffi-cient	(95% CI)	Coeffi-cient	(95% CI)	Coeffi-cient	(95% CI)
Mean CO_2 on day of survey (per 100 ppm)	0.01	(-0.15, 0.17)	0.02	(-0.14, 0.20)	-0.08	(-0.22, 0.07)	-0.06	(-0.20, 0.07)
Maximum CO_2 on day of survey (per 100 ppm)	-0.02	(-0.12, 0.08)	-0.01	(-0.11, 0.09)	-0.10	(-0.18,-0.15)	-0.09	(-0.17, 0.002)

Models adjusted for job dissatisfaction, age, gender, smoking, and shared workspace (see Table 5 for covariates) and also mean indoor temperature on day of survey.

Discussion

The objective of this study was to quantify the relationships of VRs in California office buildings with occupant outcomes that were hypothesized, based on prior research, to be increased by lower VRs: respiratory illnesses and respiratory illness-related absences, building-related symptoms, and dissatisfaction with indoor air quality and odors. No statistically significant relationships were found, except for a small significantly positive association of the alternative VR metric and respiratory illness-related absence, contrary to hypotheses. Given that over 35 associations were estimated, one or two statistically significant association would have been expected simply by chance, without true underlying relationships. Some nonsignificant tendencies, such as for the CO_2 metrics and acceptability of odors measured on a continuous scale, were in the direction hypothesized from prior knowledge. In contrast, however, some nonsignificant tendencies, such as for the CO_2 metrics and the illness absence-related outcomes, were in directions opposite those hypothesized from limited prior findings.

The overall weakness of these signals suggest that actual relationships, within the range of VRs included in this study, were either absent or so weak that greater statistical power would be necessary to detect them. VRs were uniformly high over time in almost all study spaces. For the three-month median VRs in each study space, used in illness absence analyses, only one (6.9 L/s per person) was below 13; others ranged from 13.1-65.8 L/s per person. Most VR data in illness absence analyses (between the tenth and ninetieth percentiles) were between 16 and 42 L/s per person, which is over twice to over nine times the California minimum VR standard. For the daily VR values corresponding to the CO_2 values used in analyses of symptoms and perceived air quality, the tenth-to-ninetieth percentile range was 13 to 45 L/s per person. Thus this study was unable to assess relationships with VRs considered substandard, and could only compare high with very high VRs, a range in which indoor contaminant levels are highly diluted and little variation in contaminant concentration would result. The findings might in fact be interpreted as preliminary evidence for an upper bound of the range of VRs within which increased VRs may substantially reduce illness absence (about 16 L/s per person), or improve symptoms or perceived air quality (about 13 L/s per person). Establishing such bounds more firmly would require larger studies.

Many reviews have concluded that lower building VRs are associated with adverse human outcomes [1-3, 8, 11-14]. The limited available data suggest increases in absence rates and respiratory illnesses as ventilation rates are reduced [6, 7]. Milton et al. reported lower rates of illness absence in offices with 24 vs. 12 L/s per person, a contrast within the VR range of the current study. In studies of classrooms, Mendell et al. [15] found that lower VRs in the range of approximately 2-20 L/s per person were associated with significantly increased illness absence in primary school students. A large number of office studies generally shows worsening of SBS symptoms and perceived air quality at lower VRs below about 20 or 25 Ls^{-1} per person [1-3]. This study did not find such relationships, but daily VRs in this study were mostly above 13 $L\ s^{-1}$ per person.

Strengths and limitations

Strengths of this study include the prospective design, following office workers over four seasons during a full year, which allowed within-person analyses and reduced statistical confounding by personal factors; use of daily VRs or CO_2 in each study space based on real-time CO_2 measurements every day over a year instead of the usual short-term measurements over one or several days; and use of frequently recalibrated CO_2 sensors to estimate VRs, successfully keeping sensor drift within 5%.

The study had multiple limitations. A primary limitation was the insufficient statistical power, with a study size too small to detect the small differences in exposure and effects expected within the observed range of VR. The sample size was smaller than planned, a combined result of the inability to recruit the desired number of buildings (due to the unwillingness to participate of management in most buildings contacted), and the very low survey participation rates of occupants in participating buildings, despite financial incentives. Findings may apply only to public-sector buildings, as most contacted in the private sector declined to participate, and to the minority of occupants who participated in each study space. Respiratory illness episodes and respiratory illness-related work absence were assessed only by questionnaire, and retrospectively for the prior three month period. Prospective gathering of this data from occupants would have been more accurate, but also more onerous and susceptible to nonresponse.

Estimation of VRs involved many potential sources of error, as assumptions underlying use of equation 1 are often invalid: peak CO_2 levels in each space not reaching true equilibrium during many work days (resulting in overestimation of true VRs as well as random error); potential errors in measuring and estimating indoor CO_2 levels in each study space, such as from poor air mixing or nearby occupant exhalation (resulting in underestimation of VRs); the use of a fixed rather than measured outdoor CO_2 levels, which vary by location and time of day, in calculating VRs (resulting in random VR errors); possibly inaccurate assumptions about CO_2 generation rate; and the assumption of unchanging VR per person during each day in each space, despite occupancy changes, and part-day use of economizers. VRs calculated from the alternative metric rely on fewer assumptions, but only represent VRs during the selected short time periods.

Implications

Ventilation rate standards are still largely based on decades-old studies of the amount of ventilation needed to satisfy 80% of visitors to a space with the occupants as the dominant pollutant source [16, 17]. There is no explicit analysis underlying the current standards that considers health risks from exposure to indoor air pollutants, potential impacts to workers' performance, or energy and other associated cost considerations. Further research is still necessary to provide scientific support for health-protective building VR standards.

The uniformly high VRs in the California office buildings in this study are presumably due largely to the combination of generally moderate climates and use of economizer systems that bring in large volumes of outdoor air (for "free cooling") during periods of moderate outdoor temperatures. However, even the estimated minimum VRs observed in these buildings (when presumably operating without economizers) also generally exceeded the minimum requirement in the California Title 24 standard, suggesting poor control of minimum VRs. (Some proportion of these high VR estimates was, as discussed previously, likely due to overestimation based on daily peak CO_2 levels.) Future assessments of the relationships studied in this project thus need to include geographic areas with more severe climates and thus lower VRs. Future studies should also take into account the possibility that in some locations very high VRs may introduce substantial amounts of outdoor air pollutants into the indoor environments, with adverse respiratory effects.

The conduct and findings of the present study also provide other lessons for future studies on this topic. Substantial time and effort will be necessary to successfully recruit a sufficiently large sample of buildings. Within study buildings, either substantially increased financial incentives or other novel approaches will be necessary to achieve desired response rates, especially in a prospective study with repeated surveys. Use of prospectively collected diary data from occupants on respiratory infections, or even more objectively, employer-provided illness absence data, would improve the quality of these data. Improved methods to estimate VRs need to be developed and validated. (Although tracer gas methods can measure VRs more accurately, they are not practical for year-long studies in multiple buildings.) Increased introduction of outdoor air pollutants into buildings by higher VRs should be considered in data collection and analyses, especially with higher VRs. To the extent that specific indoor office pollutants that might vary with VR or even without VR could influence respiratory illness, measurement of these over time would reduce statistical noise and allow greater power in smaller studies; however, such measurements could be quite costly.

The prospective observational design used in the present study, with some of the improvements mentioned above, would be suitable for the questions of interest here, as it is relatively economical and it allows greater generalizability of findings than controlled chamber studies, which also could not study respiratory infections in office populations over extended periods. However, field intervention studies comparing existing low and experimentally raised VRs, if done for extended periods in consideration of seasonal illness patterns, and in large populations to achieve sufficient power, could provide additional useful information on VR and respiratory infections.

In addition, developing increased knowledge about physical mechanisms of indoor transmission of respiratory infections would help focus future field studies on determinants of transmission. It is still uncertain how much of this disease transmission occurs by each of four possible modes: a direct contact mode (person-to-person contact); an indirect contact mode (from physical contact with surfaces contacted by those infected); a droplet mode (the impact of large droplets from coughing and sneezing on others quite nearby); or by long-range airborne transmission (through very small droplet aerosols produced by drying of larger aerosols expelled in coughing or sneezing). The VR may influence transmission of infectious respiratory disease by changing indoor concentrations of the very small aerosols associated with long-range airborne transmission or possibly by changing humidity or concentrations of air pollutants that might affect either the period of viability of infectious particles or people’s susceptibility to infection. However, all of the disease transmission mechanisms are coupled, e.g., increased long-range airborne transmission would result in more sick occupants who could transmit infections via other transmission mechanisms. A number of infectious agents are involved in the mix of infectious diseases in an office population, and each may be primarily transmitted through different mechanisms. Improved understanding of these processes will help inform field research in buildings.

Conclusions

This study found (with one exception) no statistically significant relationships between VRs in these California commercial buildings and occupant outcomes hypothesized to be increased by lower VRs: respiratory illnesses and respiratory illness-related absences, building-related symptoms, and dissatisfaction with indoor air quality and odors. (The exception was one small, significantly positive association of the alternative VR metric with respiratory illness-related absence, contrary to hypotheses, but a possible chance finding due to the large number of analyses.) The overall lack of relationships was apparently due to the almost uniformly very high VRs in the studied spaces over the year of the study. The three-month median VRs in the study spaces, with one exception, ranged from 13.1 to 65.8 L/s per person, which is from almost twice to over nine times the California minimum VR standard of 7 L/s (15 cfm) per person. Thus this study had limited contrast in exposures, and could compare only high with very high VRs, a range in which little variation in contaminant concentration and occupant effects would result.

This study provided some limited data on actual minimum VRs in California office buildings (during non-use of economizers), suggesting that, to the extent the studied buildings are representative, these VRs are usually substantially higher than required in the current applicable standard. This conclusion is limited by potential errors of overestimation for VRs in this study.

List of abbreviations

American Society of Heating, Refrigerating and Air-conditioning Engineers	ASHRAE
Bay Area	Bay Area
carbon dioxide	CO_2
Central Valley	CV
cfm	cubic feet per minute
generalized estimating equation	GEE)
heating, ventilating, and air-conditioning	HVAC
incident rate ratios	IRR
indoor air quality	IAQ
Minimum Efficiency Reporting Value	MERV
odds ratio	OR
ppm	parts per million
temperature	T
relative humidity	RH
sick building syndrome	SBS
South Coast	SC
ventilation rate	VR

References

1. Seppänen O, Fisk WJ, Mendell MJ: **Association of ventilation rates and CO_2 concentrations with health and other responses in commercial and institutional buildings**. *Indoor Air* 1999, **9**(4):226-252.
2. Wargocki P, Sundell J, Bischof W, Brundrett G, Fanger PO, Gyntelberg F, Hanssen SO, Harrison P, Pickering A, Seppanen O *et al*: **Ventilation and health in non-industrial indoor environments: report from a European multidisciplinary scientific consensus meeting (EUROVEN)**. *Indoor Air* 2002, **12**(2):113-128.
3. Sundell J, Levin H, Nazaroff WW, Cain WS, Fisk WJ, Grimsrud DT, Gyntelberg F, Li Y, Persily AK, Pickering AC *et al*: **Ventilation rates and health: multidisciplinary review of the scientific literature**. *Indoor Air* 2011, **21**(3):191-204.
4. Mendell MJ, Apte MG: **Balancing energy conservation and occupant needs in ventilation rate standards for "Big Box" stores and other commercial buildings in California: Issues related to the ASHRAE 62.1 Indoor Air Quality Procedure**. In. Berkeley, CA: Lawrence Berkeley National Laboratory: LBNL-6200E; 2013.
5. Bluyssen PM, de Oliveira Fernandes E, Groes L, Clausen G, Fanger PO, Valbjorn O, Bernhard CA, Roulet CA: **European indoor air quality audit project in 56 office buildings**. *Indoor Air* 1996, **6**:221-238.
6. Li Y, Leung GM, Tang JW, Yang X, Chao CYH, Lin JZ, Lu JW, Nielsen PV, Niu J, Qian H *et al*: **Role of ventilation in airborne transmission of infectious agents in the built environment - a multidisciplinary systematic review**. *Indoor Air* 2007, **17**(1):2-18.
7. Milton DK, Glencross PM, Walters MD: **Risk of sick leave associated with outdoor air supply rate, humidification, and occupant complaints**. *Indoor Air* 2000, **10**(4):212-221.
8. Fisk WJ, Mirer AG, Mendell MJ: **Quantitative relationship of sick building syndrome symptoms with ventilation rates**. *Indoor Air* 2009, **19**(2):159-165.
9. Dutton SM, Fisk WJ: **Energy and indoor air quality implications of alternative minimum ventilation rates in California offices**. *Building and Environment* 2014, **(in press)**.
10. ASTM: **ASTM D6245-12: Standard guide for using indoor carbon dioxide concentrations to evaluate indoor air quality and ventilation.** . In., vol. Designation D 6245-12, Vol.. 11.07. West Conshohocken, PA: American Society for Testing and Materials; 2012.
11. Godish T, Spengler JD: **Relationships between ventilation and indoor air quality: a review**. *Indoor Air* 1996, **6**(2):135-145.
12. Seppänen O, Fisk WJ, Lei QH: **Ventilation and performance in office work**. *Indoor Air* 2006, **16**(1):28-36.
13. Seppänen OA, Fisk WJ: **Summary of human responses to ventilation**. *Indoor Air* 2004, **14**(s7):102-118.
14. Wyon DP: **The effects of indoor air quality on performance and productivity**. *Indoor Air* 2004, **14**(s7):92-101.

15. Mendell MJ, Eliseeva EA, Davies MM, Spears M, Lobscheid A, Fisk WJ, Apte MG: **Association of classroom ventilation with reduced illness absence: a prospective study in California elementary schools**. *Indoor Air* 2013, **23**(6):515-528.
16. Yaglou CP, Riley EC, Coggins DI: **Ventilation requirements**. In: *ASHRAE transactions: 1936*; 1936: 133-162.
17. Berg-Munch B, Clausen G, Fanger PO: **Ventilation requirements for the control of body odor in spaces occupied by women**. *Environment International* 1986, **12**:195-199.

Additional Files

Additional file 1. Primary and alternate methods used for estimating daily ventilation rates

Introduction

The Healthy Zero Energy Buildings (HZEB) study on ventilation rate (VR) and worker illness absence collected CO_2 concentrations for one year in 16 office spaces in California. The 16 study spaces are located in nine office buildings. This document describes the procedures used to estimate VRs from the real-time indoor CO_2 data measured at 10-minute intervals.

Over the course of a workday, CO_2 concentrations typically increase as workers arrive at the office. There is usually a brief drop in concentrations during lunchtime. After that, CO_2 concentrations tend to increase again as workers return to their desks. At the end of the workday, CO_2 concentrations decrease again as workers leave the office. This varying occupancy throughout the workday is one of the challenges of estimating VR from CO_2 data. Two methods are used to estimate the ventilation rates from the CO_2 concentrations measured. Ventilation rates are estimated in units of air changes per hour, and also in terms of outdoor airflow rate per person (liters of air per second per person).

Data Collection

In each of the study spaces, concentrations of CO_2 were monitored using the Vaisala CARBOCAP® carbon dioxide transmitter GMW110 sensor, each was mounted on a wall or hung on a partition within the space. This device uses an infrared absorption sensor measuring at the CO_2 absorbance wavelength. It also uses a microchemical Fabry-Perot Interferometer (FPI) filter to make a reference measurement where no absorption occurs. This allows the device to compensate for potential light intensity variations, dirt accumulation, and other interferences in the optical path. The reported long-term stability of the GMW110 is +/- 5% of range (0 to 2000 ppm) over 5 years. The sensor also has negligible dependence on temperature (-0.35% of reading per ^{o}C) and pressure (+0.15% of reading per hPa). The device has a response time of 1 minute.

In this study, data were logged every 10 minutes at two or three locations within each study space. After three months, each sensor was replaced with a newly calibrated sensor for the next three months. The GMW110 outputs a voltage between 0 and 20 mA, which is logged using HOBO voltage data loggers. A calibration curve was used to compute the CO_2 concentrations from the recorded voltage. This calibration curve was obtained once before a sensor was deployed, and again three months later after the sensor finished sampling. Calibration was performed by placing the Vaisala CO_2 sensors in a small room, where CO_2 was injected to raise the concentrations to between 1000 and 2000 ppm. CO_2 concentration then decayed gradually over approximately 12 to 24 hours to background levels. The decay in concentrations was measured by a PPSystems CO_2 gas analyzer EGM-4, which is a high precision instrument with reported accuracy of <1% over the concentration span between 0 and 2000 ppm. The calibration curve was obtained by a best-fitted regression line that describes the relationship between the voltage output by the Vaisala and the CO_2 concentrations measured by the PPSystems gas analyzer.

Each Vaisala CO_2 sensor was used up to five times in this study in different study spaces. In between uses, the sensors were calibrated as described above. Seventy sensors were used in this study, of which 66 were used more than once. Figure 1 compares the differences in CO_2 concentrations between calibrations from the 66 sensors. Changes between calibrations were evaluated by comparing the CO_2 concentrations that a sensor reports now relative to the values that it would report using the prior calibration curve. Figure 1 shows that the Vaisala CO_2 sensors tend to report higher values after use than when the prior calibration curve was used. This is mainly caused by a tendency towards positive offsets, as shown in boxplot (a). On the other hand, the slope centers on unity, meaning that on average, sensitivity of the sensors to CO_2 concentrations remained unchanged. Dirt accumulation absorbing some of the infrared signal may be one of the causes of positive offset. The resulting change is about 10 ppm (median value) if CO_2 concentrations were at 600 ppm, as shown in Figure 1(c). But performance was worse in some of the sensors, where a gain of 40 ppm was observed in 10% of the comparisons.

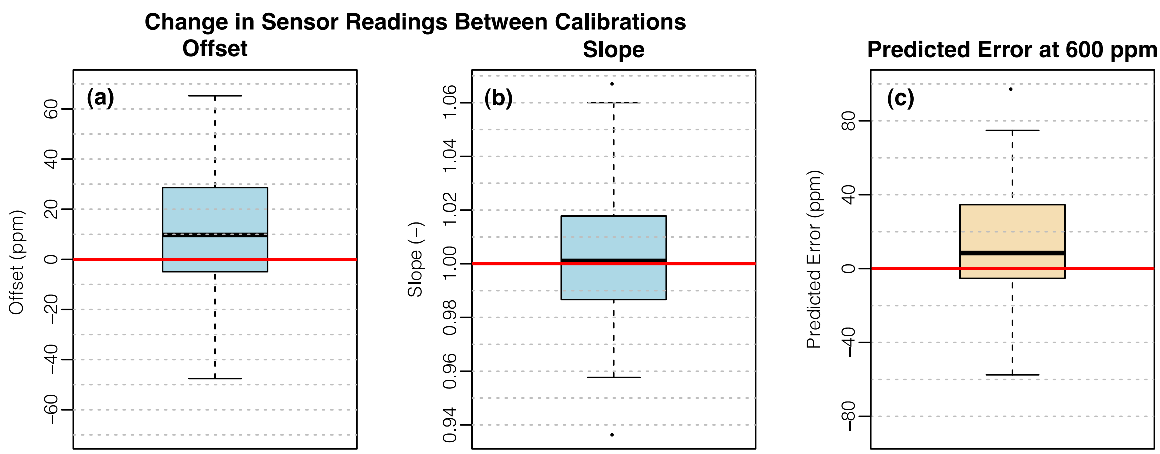


Figure 1 Change in CO_2 readings measured by the Vaisala sensors between calibrations. This analysis included a total of 177 comparisons from 66 sensors that were used more than once in this study.

Methods

CO_2 concentrations measured by multiple sensors were averaged to better represent the indoor concentrations of the study space. Two methods are considered in this analysis to estimate VR from this spatially averaged CO_2 data.

Method 1 assumes that indoor CO_2 concentrations measured each day reached steady state such that the outdoor air flow Q (m^3/h) is determined from the maximum CO_2 concentration measured indoors as follows:

$$\frac{G}{Q} = \left(C_{\max} - C_o\right)Y \quad \text{where} \quad Y = \frac{0.183 \frac{\text{g}}{\text{m}^3}}{100 \text{ ppm}} \tag{1}$$

where G (g/h) is the total CO_2 generation rate from all occupants, Q (m^3/h) is the outdoor air flow, and C_o (ppm) is the outdoor CO_2 concentration. C_{max} (ppm) is the maximum hourly averaged CO_2 concentration (that is, the maximum value of a moving 60-minute average) measured indoors between 8 am and 5:30 pm. C_o is set to equal 380 ppm in all the analyses presented here. A CO_2 generation rate, S = 18.6 L/h-person (Mudarri, 1997) is used to estimate the VR per person. This CO_2 generation rate corresponds to sedentary persons with an activity level of 1.2 met units (see ASHRAE Standards 62.2-2012 Appendix C). Substituting G = N×S into equation (1), where N is the number of occupants, gives:

$$\frac{Q}{N} = \frac{S}{\left(C_{\max} - C_o\right)} \times \frac{\text{h}}{3600\ \text{s}} \tag{2}$$

where Q/N (L/s-person) is the per-person outdoor airflow rate.

<u>Method 2</u> makes use of CO_2 data from a period when the number of office workers is roughly stable. This occurs typically in the morning, when most workers have already arrived at work and before lunchtime. During this stable period, the rate of increase in indoor CO_2 is reflective of the ventilation rate per occupants, and also the air change per hour Q/V (h^{-1}).

If the indoor air is assumed to be well mixed, then the governing equation for indoor CO_2 concentration, C, is as follows:

$$V\frac{dC}{dt} = Q\left(C_o - C\right) + \frac{G}{Y} \tag{3}$$

$$C = C_o + \frac{G}{QY} + \left(C(t_o) - \frac{G}{QY} - C_o\right)e^{-\frac{Q}{V}t} \tag{4}$$

where $C(t_0)$ is the initial indoor CO_2 concentration, V is the building volume (m^3), and C_o, Q, and G are as defined in equation (1).

Equation (4) is solved using a nonlinear least squares fitting function in R statistical software. The function uses the Gauss-Newton algorithm, which is an iterative procedure, to solve for the values of G/Q and Q/V. A solution is accepted if it met the tolerance level for convergence (10^{-5}) within the maximum number of iterations allowed (50). The starting estimate for G/Q is computed from equation (1), and Q/V = 0.5 h^{-1} is used in all cases as the initial guess.

The per-person VR and occupant density per floor area can be roughly estimated from the fitted values of G/Q and Q/V, as follows:

$$\frac{Q}{N} = \frac{SY}{G/Q} \tag{5}$$

$$\frac{N}{FA} = \frac{N}{V/H} = \frac{(Q/V)H}{Q/N} = \frac{(G/Q)(Q/V)H}{S} \times \frac{100\ \mathrm{m}^2}{Y} \qquad (6)$$

In equation (6), the factor of 100 is for computing the occupant density, N/FA, in units of number of people per 100 m^2 of floor area. A typical office ceiling height of 2.75 m (9 ft) is assumed in equation (6).

There are many cases where Method 2 did not result in reasonable estimates of G/Q and Q/V, even though the convergence was achieved. Acceptability criteria is defined as p-value of the fitted Q/V parameter being less than 0.05. For this analysis, this effectively rejected unrealistic estimates of G/Q and Q/V that would result from poor fitting of the data. Each study space provided a two-hour period where occupancy was reported to be stable, typically between 9 and 11 am. In two of the sixteen study spaces (B3S2 and B3S4), it was necessary to shift the stable period from the reported times of between 9:30 and 11:30 to half an hour earlier, such that Method 2 would give reasonable estimates of ventilation rates for at least some of the days.

Equation (4) describes a steady increase in indoor CO_2 concentrations as a function of time during a stable occupancy period. It also assumes that the outdoor air flow is constant. To screen out days where the measured CO_2 did not fit these descriptions, the nonlinear parameter fitting was only performed if the CO_2 concentration measured towards the end of the two-hour stable period was at least 20 ppm higher than the beginning.

In some of the study spaces, there were substantial differences in the morning and afternoon CO_2 peak concentrations. Such morning-versus-afternoon differences are often more pronounced in certain seasons, suggesting that this likely resulted from the economizer bringing in more outdoor air for cooling when outdoor conditions were favorable. When a rise in CO_2 concentrations was observed in the afternoon, equation (4) was used to obtain another set of G/Q and Q/V parameters for that period using the same procedure as described above for the morning period. It is assumed that most people returned from lunch by 1:30 pm, and most people remained in the office until 4:30 pm. Based on this assumption, the afternoon stable period is set to start when the CO_2 concentration was the lowest between 1:30 and 2 pm, and end when the CO_2 concentration was the highest between 4 and 4:30 pm.

When estimates of G/Q and Q/V were successfully obtained for both morning and afternoon, estimates from the two periods were averaged to give a daily estimate. If Method 2 only gave acceptable estimates for either the morning or afternoon, G/Q of the remaining period was estimated using Method 1. For example, if Method 2 successfully estimated the values of G/Q and Q/V for the morning but not the afternoon, the afternoon G/Q was estimated using equation (1), and the per-person outdoor airflow rate, Q/N, was estimated by equation (5). The air changes per hour can also be approximated by assuming that occupant density was about the same before and after lunch. In this example, Q/V for the afternoon period can be estimated using equation (6) and assuming that the value of N/FA that was determined from the morning period also applied for the afternoon. This procedure allows an estimate of Q/N and Q/V for the afternoon period even when Method 2 failed to converge, so that a daily estimate can be computed by taking the average of the two periods.

Additional file 2. Occupant survey questionnaires

Note: All questions in the below initial survey were repeated in each recurring survey, except questions 8.1 through 8.5, which were asked only in the initial survey.

<u>Important</u> –

- **Please complete this survey at *your usual workstation at work*, and answer the questions about *the indoor environment there*.**
- **It will probably take you less than 5 minutes.**
- **We would like you to answer all the questions. However, you can skip a question if you do not want to answer it.**
- **To skip a question, check "*no answer*" and go to the next question.**

Work-Related Factors

1.1. On average, how many *hours each week* do you work in this building?

Please choose ONE response:
❍ 10 hours or less
❍ 11-20 hours
❍ 21-40 hours
❍ More than 40 hours
❍ *no answer*

2.2. Which best describes the space in which your current workstation is located?
For this questionnaire, your "workstation" is the place (desk, cubicle, office, etc) where you do the majority of your work.

Please choose ONE response:
❍ Enclosed office, private
❍ Enclosed semi-private office, shared with other people
❍ Open office space, with or without cubicles or partitions
❍ Other
❍ *no answer*

[This question appears only for those who answered 'Other' to question '4.2 ']
1.2.1. Please specify "Other" workstation:

Please write your answer here:

[This question appears only for those who answered 'Enclosed semi-private office' or 'Open office space with or without partitions' or 'Other' to question '4.2 ']

1.2.2. How many people work in the room in which your workstation is located (including yourself)?

Please choose ONE response:

❍ 2-3
❍ 4-7
❍ 8 or more

1.3. How stressful is your job?

Please choose ONE response:

1 not at all stressful	**2**	**3**	**4**	**5**	**6**	**7 extremely stressful**	*no answer*
❍	❍	❍	❍	❍	❍	❍	❍

1.4. All in all, how satisfied are you with your job?

Please choose ONE response:

1 very satisfied	**2**	**3**	**4**	**5**	**6**	**7 very dissatisfied**	*no answer*
❍	❍	❍	❍	❍	❍	❍	❍

Health Symptoms

The following questions ask about specific symptoms people may have. For each symptom below, the row of circles represents the range of severity from **none** to **very severe.**

For the following symptom, please choose the appropriate response:
Mark the circle that represents how severe this symptom is for you *at the CURRENT TIME.*

2(a) **How severe is this symptom for you now: dry, itching, or irritated eyes?**

None	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Very Severe 10**	*no answer*
❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍

[*This question appears only for those who answered 1-10 for part a*]

2(b) **Did you have this symptom before you arrived at work today?**

Please choose ONE response:
❍ Yes
❍ No
❍ *no answer*

For the following symptom, please choose the appropriate response:
Mark the circle that represents how severe this symptom is for you *at the CURRENT TIME.*

3(a) **How severe is this symptom for you now: headache?**

None	1	2	3	4	5	6	7	8	9	**Very Severe** 10	*no answer*
❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍

[*This question appears only for those who answered 1-10 for part a*]

3(b) **Did you have this symptom before you arrived at work today?**

Please choose ONE response:
- ❍ Yes
- ❍ No
- ❍ *no answer*

For the following symptom, please choose the appropriate response:
Mark the circle that represents how severe this symptom is for you *at the CURRENT TIME.*

4(a) **How severe is this symptom for you now: unusual tiredness or fatigue?**

None	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Very Severe 10**	*no answer*
❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍

[*This question appears only for those who answered 1-10 for part a*]

4(b) **Did you have this symptom before you arrived at work today?**

Please choose ONE response:
❍ Yes
❍ No
❍ *no answer*

❍

For the following symptom, please choose the appropriate response:
Mark the circle that represents how severe this symptom is for you *at the CURRENT TIME.*

5(a) **How severe is this symptom for you now: congested nose?**

None	1	2	3	4	5	6	7	8	9	Very Severe 10	*no answer*
❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍	❍

[*This question appears only for those who answered 1-10 for part a*]

5(b) **Did you have this symptom before you arrived at work today?**

Please choose ONE response:
❍ Yes
❍ No
❍ *no answer*

Health History

6.1. Have you ever been told *by a doctor* that you have or had any of the following?

Please choose ALL responses that apply:

- ❍ Asthma
- ❍ Eczema
- ❍ Hay fever (pollen allergy)
- ❍ Allergy to dust
- ❍ Allergy to mold
- ❍ None of the above
- ❍ *no answer*

[This question appears only for those who answered "Asthma" to question '3.1']

3.1.1. Do you still have asthma?

Please choose ONE response:

- ❍ Yes
- ❍ No
- ❍ *no answer*

6.2. In the last 3 months, how many *episodes* have you had of infectious respiratory illness, like a cold (common cold) or flu (influenza), either mild or severe? If *one* illness lasted multiple days, count that as *one* episode.

Please choose ONE response:

- ❍ none
- ❍ 1
- ❍ 2
- ❍ 3
- ❍ 4
- ❍ 5
- ❍ 6 or more
- ❍ *no answer*

6.3. In the last 3 months, on how many days were you absent from work (for a whole day) *because of these respiratory illnesses*? Please report as well as you can remember.

Please choose ONE response:

❍ none	❍ 4
❍ 1	❍ 5
❍ 2	❍ 6 or more
❍ 3	❍ *no answer*

Satisfaction with the Current Indoor Environment

7.1: How would you rate the <u>indoor air quality</u> in this room now?

Please choose ONE response:

❍ acceptable
❍ unacceptable
❍ *no answer*

[This question appears only for those who answered "acceptable" for Question 1.1]

7.1a. **How would you rate the indoor air quality in this room now?**

Please choose ONE response:

Just barely acceptable 1	**2**	**3**	**4**	**5**	**6**	**Completely acceptable 7**	*no answer*
❍	❍	❍	❍	❍	❍	❍	❍

[This question appears only for those who answered "unacceptable" for Question 1.1]

7.1b. **How would you rate the indoor air quality in this room now?**

Please choose ONE response:

Just barely unacceptable 1	**2**	**3**	**4**	**5**	**6**	**Completely unacceptable 7**	*no answer*
❍	❍	❍	❍	❍	❍	❍	❍

7.2. How would you rate the <u>odors</u> in this room today?

Please choose ONE response:

- ❍ acceptable
- ❍ unacceptable
- ❍ *no answer*

[This question appears only for those who answered "acceptable" for Question 1.2]

7.2a. **How would you rate the odors in this room today?**

Please choose ONE response:

Just barely acceptable 1	**2**	3	4	5	6	**Completely acceptable 7**	*no answer*
❍	❍	❍	❍	❍	❍	❍	❍

[This question appears only for those who answered "unacceptable" for Question 1.2]

7.2b. **How would you rate the odors in this room today?**

Please choose ONE response:

Just barely unacceptable 1	**2**	3	4	5	6	**Completely unacceptable 7**	*no answer*
❍	❍	❍	❍	❍	❍	❍	❍

Demographic Factors

8.1. How *many* young children (3 years old or younger) live at your home?

<u>Please choose ONE response</u>:

- ❍ 0
- ❍ 1
- ❍ 2
- ❍ 3 or more
- ❍ *no answer*

8.2 What is your tobacco smoking status?

<u>Please choose ONE response</u>:

- ❍ Never smoked
- ❍ Former smoker
- ❍ Current smoker
- ❍ *no answer*

8.3. How old were you on your last birthday?

<u>Please choose ONE response</u>:

- ❍ Under 20
- ❍ 20-29 years
- ❍ 30-39 years
- ❍ 40-49 years
- ❍ 50-59 years
- ❍ Over 59 years
- ❍ *no answer*

8.4. Are you:

Please choose ONE response:

- ❍ Male
- ❍ Female
- ❍ *no answer*

8.5. What is the highest grade you completed in school?

Please choose ONE response:

- ❍ Less than high school graduate
- ❍ High school graduate
- ❍ Some college
- ❍ College degree
- ❍ Graduate degree
- ❍ *no answer*

Thank you for completing this survey.

Submit Your Survey

Additional file 3. Description of analysis models, with exposure variables and covariates

Outcomes	Statistical Model	Exposure Variables	Covariates in Adjusted Models
Number of respiratory illness episodes in prior 3 months; Number of days of respiratory illness-related work absence in prior 3 months	Zero-inflated negative binomial, clustered on person and space	Median over prior 3 months of daily VR+++ (before day of individual's survey)	Smoking, young children in home, respiratory illness season***, number of people sharing workspace;
		Median over prior 3 months of daily mean indoor CO_2	“
		Median over prior 3 months of daily maximum indoor CO_2*	“
	Secondary model: dichotomized as 0, >0 – logistic regression	(same three exposure variables as above)	“
Symptom severity (4 symptoms)	Continuous scale 0-10 -- zero-inflated negative binomial, clustered on person and space	Mean CO_2 on day of survey; maximum CO_2 on day of survey	Mean temperature on day of survey, job dissatisfaction, age, gender, education, smoking, number of other people in workspace, any prior symptom, any allergic history, current asthma,
	Secondary model - severity dichotomized at 0, >0 –logistic regression with GEE, clustered on person and space	“	“
Acceptability of air quality; Acceptability of odors	Dichotomous outcome – logistic regression, with GEE, clustered on person and space	“	Mean temperature on day of survey, job dissatisfaction, age, gender, smoking, number of other people in workspace,

Outcomes	Statistical Model	Exposure Variables	Covariates in Adjusted Models
	Continuous outcome – linear regression with GEE, clustered on person and space	“	Same as dichotomous outcome model

* maximum sliding 15-minute average CO_2 over the workday hours of 830 a.m.-530 p.m.
** includes only symptoms beginning at work
*** if illness reporting period (3-month period prior to survey) within October—April
****in NB model component; in ZI model component included only CO_2, season, number people in work area, and hours worked per week
[+++] Primary models estimate VR from peak daily CO_2; secondary models estimate VR from curve-fitting algorithm; both described in Additional file 1.

Additional file 4. Occupant responses

Study Space	Number of occupants	Number (proportion) responding per survey*				Total number (proportion) of surveys	
		Survey 1	Survey 2	Survey 3	Survey 4	Total received	Total eligible**
Incentives							
2a	140	56 (40%)	41 (29%)	42 (30%)	35 (25%)	174 (31%)	170 (30%)
2b	127	48 (38%)	39 (31%)	32 (25%)	27 (21%)	146 (29%)	132 (26%)
3a	71	31 (44%)	26 (37%)	23 (32%)	29 (41%)	100 (35%)	95 (33%)
3b	68	25 (37%)	20 (29%)	17 (25%)	12 (18%)	74 (27%)	66 (24%)
3c	100	43 (43%)	35 (35%)	31 (31%)	27 (27%)	136 (34%)	125 (31%)
3d	33	16 (48%)	15 (45%)	13 (39%)	11 (33%)	55 (42%)	54 (41%)
5a	61	25 (41%)	17 (28%)	20 (33%)	18 (30%)	80 (33%)	79 (32%)
5b	115	49 (43%)	37 (32%)	35 (30%)	26 (23%)	147 (32%)	139 (30%)
7	86	17 (20%)	13 (15%)	12 (14%)	13 (15%)	55 (16%)	54 (16%)
8b	114	22 (19%)	19 (17%)	15 (13%)	15 (13%)	71 (16%)	55 (12%)
8c	50	18 (36%)	16 (32%)	14 (28%)	10 (20%)	58 (29%)	57 (29%)
9	21	6 (29%)	3 (14%)	3 (14%)	NA	12 (19%)	10 (16%)
No incentives							
4	74	20 (27%)	15 (20%)	14 (19%)	12 (16%)	61 (21%)	60 (20%)
6	64	18 (28%)	12 (19%)	11 (17%)	5 (8%)	46 (18%)	40 (16%)
No incentives but local competition							
1a	53	22 (42%)	20 (38%)	20 (38%)	15 (28%)	77 (36%)	75 (35%)
1b	41	22 (54%)	13 (32%)	10 (24%)	8 (20%)	53 (32%)	46 (28%)
Incentives total	986	356 (36%)	281 (28%)	257 (26%)	223 (23%)	1,108 (28%)	1,036 (26%)
No incentives total	138	38 (28%)	27 (20%)	25 (18%)	17 (12%)	107 (19%)	100 (18%)
No incentives but competition, total	94	44 (47%)	33 (35%)	30 (32%)	23 (24%)	130 (35%)	121 (32%)

Overall	1218	438 (36%)	341 (28%)	312 (26%)	263 (22%)	1,345 (28%)	1,257 (26%)

* response proportion for each survey calculated as proportion of original total of occupants

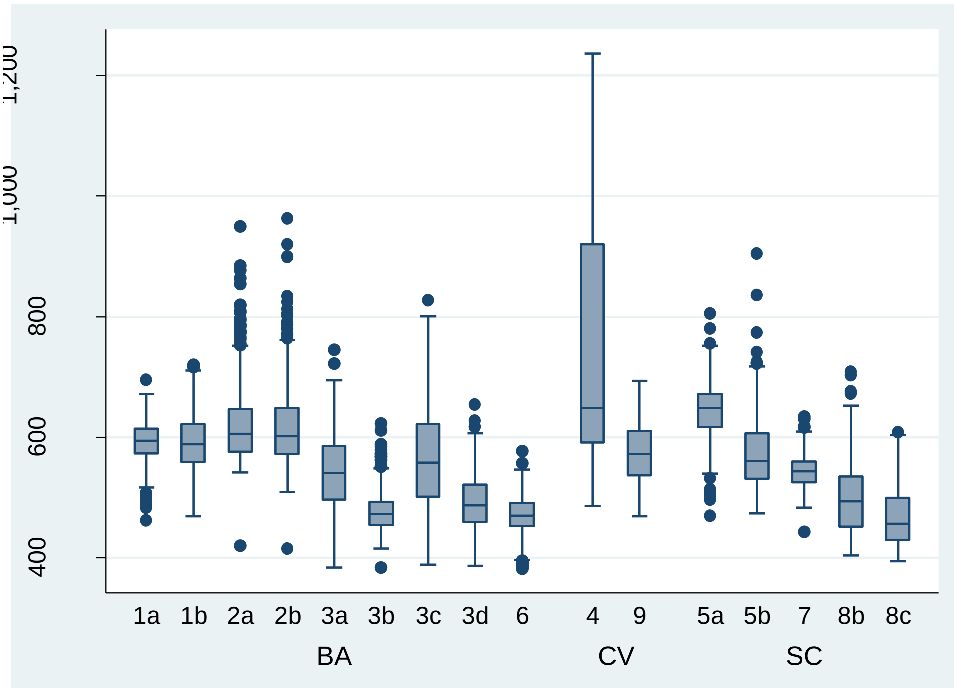
** after exclusion of surveys from occupants working in the building only 20 or fewer hours/week, and not completing the initial survey with background information

Additional file 5. Prior symptom* outcomes among respondents on day of survey**

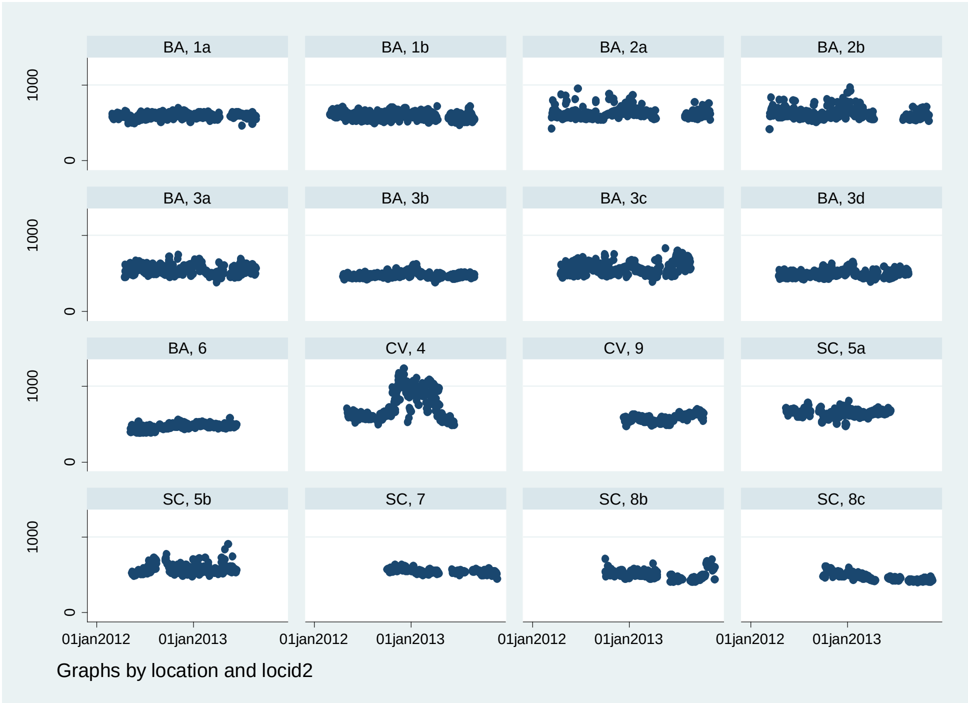
Study Space	Occupants with any symptom before work n (%)			
	eye	head	fatigue	nose
Bay Area				
1a	16 (35%)	4 (17%)	22 (55%)	17 (55%)
1b	5 (23%)	4 (36%)	8 (32%)	14 (61%)
2a	23 (25%)	15 (29%)	52 (54%)	58 (72%)
2b	33 (41%)	13 (43%)	58 (70%)	50 (81%)
3a	28 (41%)	10 (26%)	42 (67%)	40 (62%)
3b	11 (25%)	9 (26%)	10 (26%)	20 (49%)
3c	21 (22%)	16 (23%)	31 (35%)	31 (41%)
3d	29 (67%)	10 (45%)	25 (81%)	26 (84%)
6	7 (44%)	4 (67%)	15 (83%)	16 (80%)
Central Valley				
4	15 (50%)	5 (20%)	15 (48%)	14 (70%)
9	4 (44%)	0 (0%)	4 (57%)	2 (22%)
South Coast				
5a	15 (44%)	7 (47%)	24 (57%)	18 (82%)
5b	43 (52%)	15 (31%)	61 (66%)	47 (67%)
7	14 (45%)	9 (47%)	24 (73%)	18 (82%)
8b	20 (54%)	10 (67%)	14 (61%)	13 (68%)
8c	11 (26%)	4 (19%)	17 (46%)	16 (64%)
TOTAL	303 (38%)	138 (31%)	437 (56%)	411 (65%)

* symptoms are: dry, itching, or irritated eyes; headaches; unusual tiredness or fatigue; and congested nose; response scale ranges from 0 (none) to 10 (very severe)
** after all exclusions (see Additional File 4 footnote); includes data from respondents eligible for survey and who also answered both parts of the symptom question

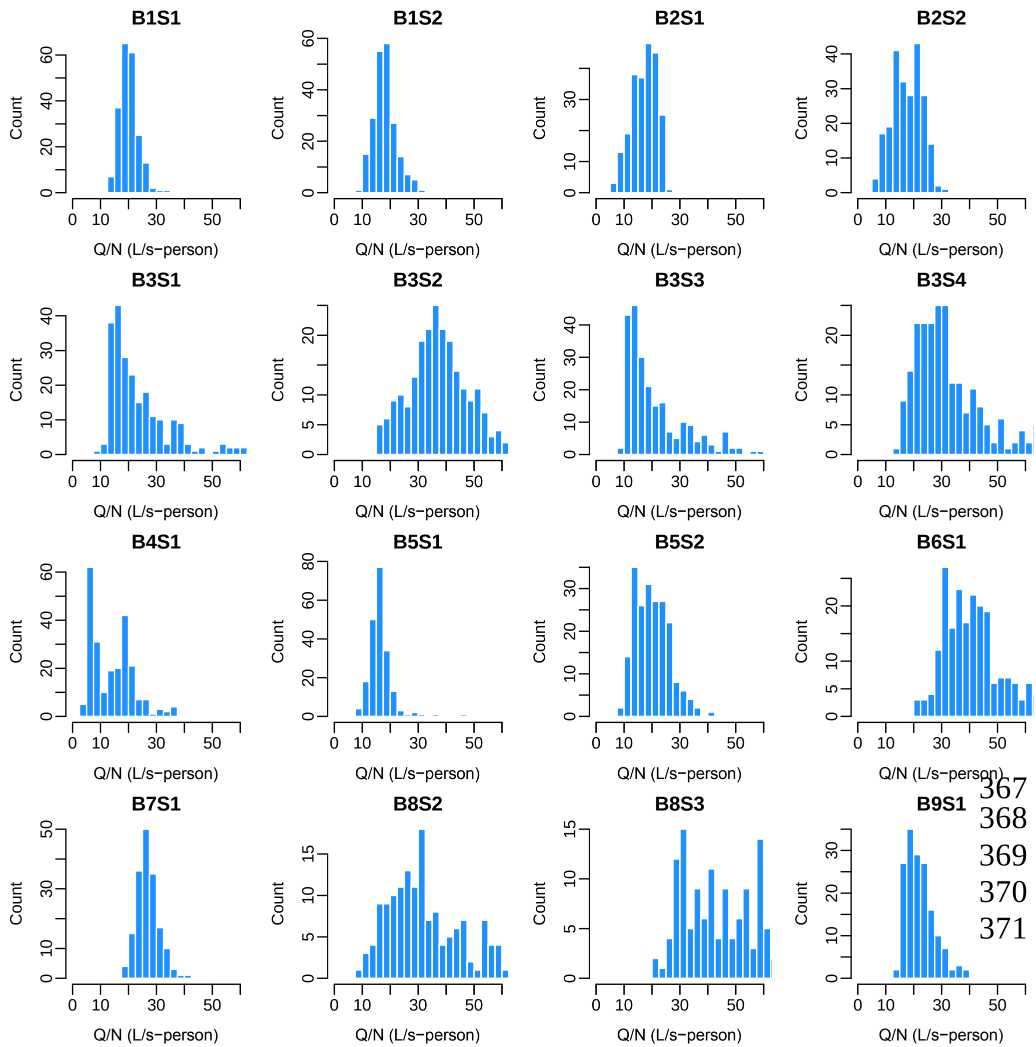
Additional file 6. Distributions of daily mean indoor CO_2 measurements, by study space grouped by climate zone



Additional file 7. Daily mean indoor CO_2 values over time, per study space grouped by climate zone



Additional file 8. Distributions of ventilation rates calculated via method 1, and estimated minimum ventilation rates from 5th percentile values.



Space	5th Percentile
B1S1	15.7
B1S2	12.1
B2S1	9.2
B2S2	9.3
B3S1	13.2
B3S2	20.8
B3S3	11.1
B3S4	18.0
B4S1	5.4
B5S1	11.7
B5S2	11.9
B6S1	27.9
B7S1	21.0
B8S2	15.4
B8S3	27.6
B9S1	16.2
Average	15.4

Additional file 9. Outcome summaries by categories of respondent characteristics

	Mean number respiratory infection episodes in prior 3 mo	Mean number respiratory illness-related work absences in prior 3 mo	Proportion reporting any symptom*				Mean score for acceptability	
			Eye	Headache	Fatigue	Nose	IAQ	Odor
Hours worked each week in building:								
21-40	0.94	0.87	0.40	0.14	0.43	0.38	4.63	5.54
>40	0.92	0.71	0.47	0.17	0.51	0.42	4.60	5.55
Number of others sharing workspace:								
0	0.74	0.61	0.41	0.19	0.43	0.41	5.24	5.81
1-2	1.03	1.06	0.37	0.23	0.54	0.34	3.93	4.62
3-6	1.06	0.98	0.67	0.19	0.48	0.41	2.90	3.94
7 or more	0.95	0.79	0.44	0.14	0.48	0.40	4.59	5.63
Job stress (1=not at all, 7=extremely):								
1-2	0.98	0.43	0.30	0.14	0.24	0.35	5.63	6.00
3-4	0.91	0.84	0.39	0.10	0.40	0.40	4.44	5.53
5-7	0.93	0.78	0.46	0.17	0.52	0.41	4.61	5.53
Job dissatisfaction (1=very satisfied, 7=very dissatisfied):								
1-2	0.86	0.57	0.41	0.13	0.35	0.37	5.11	6.00
3-4	0.89	0.84	0.43	0.17	0.57	0.46	4.20	5.19
5-7	1.07	0.99	0.47	0.17	0.55	0.39	4.47	5.41

Number of children up to age 3 years at home**:								
0	0.89	0.77	0.45	0.15	0.47	0.42	4.58	5.53
1-2	1.16	0.93	0.39	0.17	0.51	0.31	4.83	5.60
3 or more	0.63	0.37	0.40	0.27	0.29	0.63	4.42	5.28
Smoking status**:								
Never	0.95	0.81	0.44	0.16	0.49	0.40	4.57	5.51
Former	0.79	0.74	0.45	0.17	0.44	0.40	4.57	5.55
Current	0.80	0.54	0.33	0.09	0.40	0.40	5.90	6.06
Age**								
Under 30	1.00	0.59	0.47	0.15	0.60	0.41	4.19	5.47
30-39	0.92	0.81	0.42	0.18	0.51	0.37	5.17	5.74
40-49	1.01	0.86	0.41	0.14	0.38	0.39	4.67	5.53
50 or over	0.84	0.83	0.48	0.16	0.45	0.47	4.21	5.37
Gender**								
Female	1.03	0.99	0.49	0.21	0.58	0.40	4.10	5.35
Male	0.84	0.59	0.39	0.12	0.39	0.41	5.08	5.71
Education completed**								
High school	1.89	1.82	0.60	0.00	0.75	0.64	2.11	3.96
College degree	0.87	0.82	0.45	0.16	0.48	0.40	4.63	5.49
Graduate degree	0.96	0.70	0.42	0.15	0.47	0.40	4.72	5.66
Prior medical diagnoses:								
Asthma	1.35	1.12	0.57	0.23	0.57	0.44	4.57	5.38
Current asthma	1.51	1.14	0.60	0.22	0.60	0.48	4.32	5.44
Eczema	0.92	0.74	0.43	0.15	0.51	0.39	4.77	5.23
Hay fever ++	1.14	1.04	0.54	0.16	0.51	0.50	4.13	5.38
Dust allergy	1.34	1.22	0.51	0.20	0.54	0.49	3.96	5.26
Mold allergy	1.33	1.26	0.62	0.19	0.56	0.55	3.35	5.00
Any allergy	0.75	0.63	0.34	0.14	0.44	0.36	4.87	5.71
No allergy/asthma	1.12	0.95	0.52	0.17	0.51	0.45	4.34	5.33

Note: All numbers exclude those not working >20 hours/week
* after exclusion of those with a prior symptom

** For these variables, questions were asked only on the first survey, and responses were retained for analyses of later surveys
+ with or without cubicles or partitions
++ pollen allergy

Additional file 10. Adjusted and unadjusted associations between CO_2 and ventilation rates in the prior three months and respiratory illness outcomes, estimated from logistic regression models)

	Number of respiratory infection episodes in prior 3 months				Number of respiratory illness-related work absences in prior 3 months			
	unadjusted		Adjusted[#]		unadjusted		adjusted[#]	
	OR	(95% CI)	OR	(95% CI)	OR	(95% CI)	OR	(95% CI)
Median of daily CO_2 mean, prior 3 months	1.08	(0.91, 1.30)	0.97	(0.79, 1.18)	1.14	(0.95, 1.35)	0.97	(0.79, 1.19)
Median of daily CO_2 maximum, prior 3 months	1.003	(0.89, 1.13)	0.94	(0.82, 1.08)	1.06	(0.94, 1.19)	0.98	(0.85, 1.13)
Median of daily estimated VR, prior 3 months	0.99	(0.98, 1.01)	1.001	(0.99, 1.02)	0.99	(0.98, 1.01)	1.003	(0.98, 1.02)

[#] Models adjusted for: smoking, young children in home, people sharing workspace, respiratory illness season (illness reporting period in October—April); see Table 5.