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Impact of Independently Controlling Ventilation Rate per Person and Ventilation Rate per Floor Area on Perceived Air Quality, Sick Building Symptoms and Decision Making

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Table of Contents

Abstract v
Objectives vi
Introduction 1
Study Methods 2
Overview 2
Subject recruitment 3
Experimental Design and Scheduling 4
Design and operation of the test facility 7
Measuring Environmental Conditions during Testing 9
Ventilation Rate 9
Volatile Organic Compounds (integrated samples) 10
Volatile Organic Compounds (real-time measurements) 11
Low Molecular Weight Carbonyls 11
Acetic Acid 12
Particulate Matter 12
Ozone 12
Carbon Dioxide 13
Temperature and Relative Humidity 13
Measuring Human Outcomes 13
Questionnaire Data for PAQ and SBS symptoms 13
Simulation Measuring Decision-Making Performance 14
Data Analysis 16
Environmental Data 16
Strategic Management Simulation Data 16
Questionnaire Data 17
Results 17
Environmental conditions in experimental sessions 17
Questionnaire results 41
SMS Decision Making Performance 47
Discussion 54

DRAFT

Synthesis and interpretation of findings 54
PAQ and SBS assessment 54
SMS Decision-Making Performance Assessment 55
Limitations 57
Future work 57
References 58
Appendix A. On-line Survey Instrument for PAQ, SBS, Health History, and Demographic information used during HZEB Lab Study on Office Ventilation Strategies. 60
Appendix B. Particle number concentration data 67
Appendix C. Summary figures of response for each PAQ/SBS variable 74

DRAFT

Abstract

Ventilation standards for commercial buildings set a minimum required outdoor air ventilation rate per occupant to control indoor levels of pollutants including bioeffluents from occupants and their activities and/or a minimum ventilation rate per unit floor area to control indoor levels of pollutants from the building and products used in the building. However, few data are available to indicate the relative importance of controlling occupant-related or building-generated pollutants with ventilation. An experimental facility was designed that allows the independent control of ventilation per occupant and ventilation per floor area in a simulated office environment. Two studies were conducted to measure the impact of either occupant or floor-area based ventilation separately. Thirty-two subjects were assigned to groups of four and each group experienced two different blinded ventilation scenarios in different sequences, with four groups participating in each study. Each test condition lasted four hours and each group experienced two conditions per day in a self-paired study design. The order of presentation of test conditions, day of testing and gender were balanced. Temperature, relative humidity and airflow rates were controlled and logged continuously. Particle number concentrations, size resolved particle mass concentrations, CO_2 and ozone were logged continuously. Short-term integrated measurements of volatile organic compounds were collected during each session. The subjects were surveyed using on-line instruments to assess perceived air quality (PAQ), sick building syndrome (SBS) symptoms and decision-making performance. The resulting data were analyzed using statistical models. Neither changing the ventilation rate per person nor changing the ventilation rate per floor area, in the range and for the duration tested here, had consistent statistically significant effects on PAQ or SBS symptoms. However, moderate reductions in either occupant-based ventilation rate or floor-area based ventilation rate had a significant and independent negative impact on a range of decision-making measures. These results provide compelling evidence that changes in outdoor air ventilation rate influences human performance even when PAQ and SBS symptoms are unaffected. The results for occupant-based ventilation agree with previous work that measured the relationship between CO_2 concentration and decision-making performance in an office setting, with CO_2 levels modified by injection of pure CO_2. The results for area-based ventilation represent the first controlled human study showing a statistically significant reduction in decision-making performance as a function of decreased ventilation rate per unit floor area of office space. Further study should focus on quantifying the influence of outdoor air on cognitive function across a wider range of ventilation settings to identify the optimal ventilation rate for occupancy and for floor area.

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Objectives

This project is part of a larger study designed to provide a stronger scientific basis for ventilation standards that balance energy efficiency with provision of acceptable indoor environments for occupants. The specific objective of this project is to measure human outcomes including perceived air quality (PAQ), sick building syndrome (SBS) symptoms, and decision making performance as affected independently by either outdoor-air ventilation rate per occupant or outdoor-air ventilation rate per unit of floor area in an office environment

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Introduction

California's Title 24 requires that a building be provided *the larger of* a minimum ventilation rate (VR) per occupant or a minimum VR per unit floor area (California Energy Commission 2008). The ASHRAE ventilation standard for commercial buildings requires provision of a minimum VR per occupant *added to* a minimum VR per unit floor area (ASHRAE 2010). The intent of both standards is to assure that the VR is sufficient to maintain acceptable indoor concentrations of occupant-generated pollutants (e.g., bioeffluents, personal care products, pollutants from human activities) and acceptable indoor concentrations of pollutants emitted from building materials, furnishings, and the products used in buildings. This approach is rational given that people and buildings are both sources of pollutants. However, the available data for determining the relative amounts of ventilation needed to serve these two purposes are extremely limited.

Laboratory studies completed decades ago in conditions with occupants as the dominant pollutant source, but with minimal information on other sources, found that PAQ diminished as VR per occupant decreased (Janssen 1992). Most of the more recent research has been performed in offices. This research indicates that, on average, higher VRs per person are associated with improved PAQ, reduced SBS symptoms, and improved work performance (Seppänen et al. 1999; Fisk et al. 2009; Sundell et al. 2011). However, these studies did not examine whether VR per floor area was also associated with PAQ, SBS symptoms, and performance. A small laboratory study (Kajtar et al. 2006) found significant degradations in PAQ, and in some aspects of work performance, when CO_2 levels were increased to 3000 ppm or higher by injecting pure CO_2 into the air with other factors remaining constant. A recent laboratory study (Satish et al, 2012) found a significant decrease in decision-making performance, but no effect on SBS symptoms, when ultrapure CO_2 was added to increase CO_2 concentrations to 1000 or 2500 ppm, relative to a base case with CO_2 at 600 ppm suggesting that CO_2 should be considered a contaminant and not just a surrogate for other bioeffluents. Measuring human outcomes related to either exposure to occupants' emissions or exposure to buildings' emissions requires a highly controlled test environment that carefully separates the two pollutant sources and allows for independent control of each source. It would be very difficult to examine the relative importance of ventilation per occupant and ventilation per floor area during intervention studies conducted in field settings, because neither occupancy nor the building-related sources of pollutants can be controlled with other factors (i.e. building type, age, contents, occupant density) held constant or balanced.

Laboratory studies can separately vary VR per occupant and VR per floor area and enable precisely controlled VR and environmental conditions for studying the relationship between VR and its impact on occupants. The study design can be balanced to cancel out effects of factors other than VRs that may affect the occupant outcomes. The main disadvantage of laboratory studies is that they are a simulation of field conditions and one can never be certain of how

DRAFT

representative the results are of actual field conditions. However, this criticism also applies to intervention studies in small numbers of buildings in field settings, since the buildings in the field studies may not be representative of the larger building stock.

This project used human subjects in a controlled environment designed to simulate a recently renovated open-space office. The results were expected to provide data relevant to ventilation requirements in offices, although the resulting data on benefits of ventilation per person or per floor area were expected to be more broadly applicable. This report provides details on the study design, data collection, and findings related to sources of pollutants in occupied spaces, and the impact of each pollutant source on SBS, PAQ and decision-making performance.

Study Methods

Overview

The experimental design for this study carefully separates occupant-generated chemical emissions from building-generated chemical emissions. The design uses an adjacent pair of ventilated and conditioned rooms located within a larger thermally-conditioned building. Each room is approximately 21 m^2 with a 2 m ceiling height and is served by a dedicated and precisely controlled heating, ventilation and air conditioning (HVAC) system that provides constant room air circulation with controlled outdoor air ventilation. One of the rooms (test room) is set up to achieve very low building-related emissions and used as the test room where occupants are located during the experiments. The adjacent room (source room) is set up to simulate a recently renovated office space with newly refurbished walls, doors, ceiling and floors and furnished with office cubicles, chairs, desks, computers and a printer.

The two rooms are connected by ducts and flow control valves to allow for different mixes of air in the test room from the source room, from outdoors and from recirculated test room air. The effects of varying VRs per occupant to modify occupant-generated chemical exposures are tested by manipulating the flow rates of outdoor air and recirculated air supplied to the test room while maintaining a low and constant fraction of air from the renovated office. The effects of varying VRs per floor area to modify exposures from building materials and office equipment are tested by manipulating the fraction of outdoor air flowing to the test room that first passes through the source room, while maintaining a low and constant concentration of occupant pollutants using a high flow of outdoor air.

Groups of four subjects each were exposed to specific test conditions or ventilation scenarios during two 4-hour sessions conducted during the same day. Four days of testing were completed to study effects of changing VRs per occupant and an additional four days of testing was completed to study effects of varying VRs per floor area. The human outcomes measured during each test include 1) perceived air quality (PAQ), 2) sick building syndrome (SBS) symptoms, and 3) decision making performance. Details of the methods are provided below.

DRAFT

The following sections provide details on the recruitment process, experimental design and scheduling, design and operation of the test facility, measurement of environmental conditions during testing, measurement of human outcomes during testing, and methods used for data analysis.

Subject recruitment

A detailed human subjects protocol was prepared and submitted to the Lawrence Berkeley National Laboratory (LBNL) Institutional Review Board (IRB). The protocol was reviewed and approved by the IRB prior to recruitment and interaction with subjects.

The initial goal was to recruit 48 adult subjects, with equal number of males and females, having a typical level of known or suspected common sensitivities, while excluding subjects with special health concerns. The female population was expected to be more sensitive to changes in exposures that affect PAQ because females typically have a better sense of smell. Females and those who self-report allergy are known to report more SBS symptoms; thus, they may be more sensitive to changes in exposures related to SBS symptoms. No sub-populations are known to have decision-making performance that varies with above-average sensitivity to the environmental conditions in this research project. c

Given these recruitment goals, the study subjects were recruited primarily from University of California staff and students, with secondary recruitment from LBNL interns. The recruitment process resulted in a number of subjects not directly associated with the University of California or LBNL, but most subjects were university students or college-age adults. Children were excluded from recruitment because they are not representative of office workers. Individuals with cardiovascular disease or serious respiratory diseases, such as chronic obstructive pulmonary disease and asthma were also excluded. Individuals with these diseases are not know to have increased sensitivity to the factors tested in this project and their inclusion may complicate interpretation of the results from the small sample of subjects. Subjects with no sense of smell and those who consider themselves highly sensitive to chemicals (uncommon in general population and might bias results of a small study) were also excluded. Allergic sensitization is highest in young adults, is only slightly associated with income, and is increased moderately in those with greater than a 12th grade education (Arbes et al 2005). Based on these considerations, our primary target population (college-age adults) was expected to have prevalence of allergy that is typical of, or slightly higher than, that of the general population.

The participating subjects were divided into eight study groups based on subjects' availability and the objective of balancing gender in each group. Each group consisted of four subjects and two alternates. The alternates (one male and one female) were scheduled for each day to ensure full participation in case of no-shows. Ultimately, only 39 subjects were recruited because several of the alternates were able to return for multiple days if they were not needed as replacements.

DRAFT

Each study group participated for one full day and during that day they experienced two of the test conditions summarized below.

Experimental Design and Scheduling

This study compares human outcomes during two separate pairs of experimental conditions. The experimental matrix is illustrated in Figure 1. The first experiment uses a combination of outdoor air and recirculated test room air to vary the concentrations of compounds related to occupant generated emissions, while maintaining constant and low concentrations of compounds related to building material emissions (conditions **1** and **2**). These two settings are used to measure the effect of VR per occupant. The second experiment uses a combination of outdoor air and air from the source room to vary the concentration of compounds related to the office space while maintaining low and constant concentrations of compounds related to occupant emissions (conditions **3** and **4**). These settings are used to measure the effect of varying VR per floor area.

Eight groups with four subjects in each group were scheduled to participate for one full day each. Four groups participated in the study of occupant generated pollutants and four groups participated in the study of building generated pollutants. The tests were scheduled for Thursday through Sunday during two consecutive weeks. Weekend days were used to facilitate scheduling for the subjects. and breaking the study into two weeks allowed for balancing the experimental design for day of the week. In addition to balancing the groups based on gender as discussed above, the study was also balanced for the day of the week and the order of treatment (Table 1).

Occupant VR experiments were conducted on Thursday and Friday of each week and floor area VR experiments were conducted on Saturday and Sunday. For example, the first Thursday and Friday of the study, Groups 1 and 2 experienced the high per-occupant VR scenario (low bioeffluent concentrations) during the morning session and low per-occupant VR scenario (high bioeffluent concentration) during the afternoon session with both sessions experiencing high per floor area VR (low concentration of office source pollutants). The following Thursday and Friday, Groups 5 and 6 experienced the same conditions but in the opposite order.

DRAFT

		Indoor air concentrations from **occupant** emissions	
		Low	High
Indoor air concentration from **office** emissions	Low	**1** **3**	**2**
	High	**4**	

Figure 1. Matrix of experimental conditions, indicated by the bold numbers, where two conditions were used each day of testing to represent either per person ventilation (conditions **1** and **2**) or floor area based ventilation (conditions **3** and **4**).

Subjects arranged their own transportation to and from the lab on their scheduled day. All four subjects in each group followed a schedule during each day of the study. The schedule is listed in Table **2**. Subjects were asked to arrive at the lab at 8:30 AM to review and sign the consent forms and get oriented to the study. If a regularly scheduled participant did not show up on time then an alternate of the same gender was selected in his/her place. Prior to entering the test office, subjects were given a unique identification code in the form of a fake e-mail address to be used during all on-line surveys and simulations.

Table 1. Balanced exposure to test conditions

		Test condition during AM and PM sessions[1]	
Subject Group	Experiment Date	AM	PM
1	Thursday, 10/4/2013	**1**	**2**
2	Friday, 10/5/2013	**1**	**2**
3	Saturday, 10/6/2013	**3**	**4**
4	Sunday, 10/7/2013	**3**	**4**
5	Thursday, 10/11/2013	**2**	**1**
6	Friday, 10/12/2013	**2**	**1**
7	Saturday, 10/13/2013	**4**	**3**
8	Sunday, 10/14/2013	**4**	**3**

[1] Refer to Figure 1 for definition of test conditions and section "Design and Operation of Test Facility" for details.

DRAFT

Table 2. Schedule of activities for one day including an AM and PM session

Time	Minutes after start of session	Activity
8:30-8:50AM		Arrive at LBNL for orientation and sign consent form
9:00		Enter office and select a desk
9:50-10:00	50–60	Perceived air quality and symptom survey (full survey)
10:00-10:50	60–110	Stretch break if needed and free time in office at desk
10:50-11:00	110–120	Perceived air quality and symptom survey (short form)
11:00-11:10	120–130	Orientation to decision making simulation survey
11:10-12:50	130–230	Decision making simulation survey
12:50-1:00PM	230–240	Perceived air quality and symptom survey (short form)
1:00-2:00		Exit office for lunch and bathroom break
2:00		Enter office returning to same desk
2:50-3:00	50–60	Perceived air quality and symptom survey (short form)
3:00-3:50	60–110	Stretch break if needed and free time in office at desk
3:50-4:00	110–120	Perceived air quality and symptom survey (short form)
4:00-4:10	120–130	Orientation to decision making simulation survey
4:10-5:50	130–230	Decision making simulation survey
5:50-6:00	230–240	Perceived air quality and symptom survey (short form)
6:00		Subjects leave office, sign attendance card and are dismissed

DRAFT

Subjects were allowed to take their personal items including backpack, books, laptops, cellphones, snacks and water into the test room with them. Subjects were asked to refrain from using strong fragrances. After entering the test room, subjects selected a desk and set up their space for the day. They were allowed to use the laptop provided on each desk or their own computers. Subjects were instructed to follow the schedule and a popup reminder on the laptop screen was used to remind subjects to complete the surveys (described later) using the laptops provided.

Subjects were monitored throughout the day through a window in the test room, and they could always contact a responsible individual by ringing a bell from inside the room. Subjects were encouraged to remain in the room for the full session but if restroom breaks were needed, they would ring the bell and be escorted to a facility in an adjacent building.

After completion of the morning session, subjects exited the test room and had lunch in an adjacent building while conditions were being set for the next session. The afternoon session followed the same schedule as the AM session, ending at 6:00 PM when subjects exited the room and signed their attendance card for compensation.

Design and operation of the test facility

The experimental facility illustrated by the schematic in Figure 2 was used to achieve independent control of the floor area VR and the occupant VR for the study. The schematic shows two adjacent rooms connected by a series of ducts and flow control valves. The test room on the left of the schematic is sparsely furnished with four small aluminum desks, ergonomic office chairs (no fabric or foam), laptop computers and occupants. The walls and ceiling of the test room are finished with fully cured Latex paint and the floor is finished with vinyl that is more than two years old. Older materials are known to have significantly lower chemical emissions compared to new materials so pollutant emissions in the test room are primarily from the occupants and their belongings.

The source room located adjacent to the test room was used to create a constant stream of indoor air that simulated a relatively new or recently renovated open office space. The source room space was created by estimating the loading factor for different materials ($m^2_{[material]}/m^3_{[space]}$) used in a typical open office plan (Carter & Zhang, 2007) and then scaling the simulated area of the space to achieve a minimum floor-area-based VR, while maintaining a high occupant-based VR for the four subjects in the adjacent room when all the outdoor air was channeled through the source room. The materials, furnishing and equipment (computers and printer) in the source room were at least 30 days old prior to testing to avoid the high and rapidly changing chemical emission rates from new materials, furnishings and equipment. The steady state concentration of office and building related pollutants was controlled by the constant outdoor air flow through the source room.

The four test conditions illustrated in Figure 1 were created by setting the specific flows in the facility to the values listed in Table 3. The total flow (L/s) through the source room (line 1) was held at 41.5 to maintain a constant concentration of office related pollutants in the exhaust from the source room. The total flow through the test room (line 5) was maintained at 48 L/s continuously to provide a constant air-flow through the room at all times.

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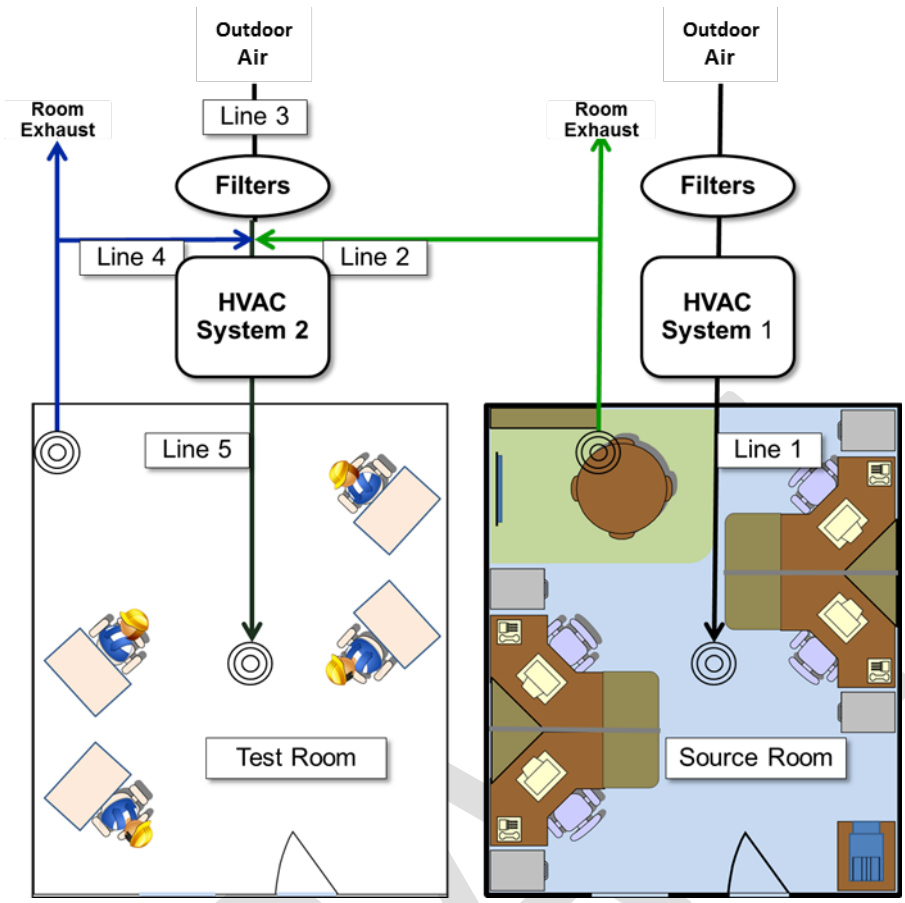

Figure 2. Schematic of the test facility with the occupied test room on the left and the building related source room simulating a recently renovated open office space on the right.

Conditions **1** and **2** simulate the impact of changing the VR per occupant in an office space without changing the VR per unit floor area. Condition **1** represented the case with a high per occupant VR and a high floor-area-based VR. It is achieved by closing line 4 (no recirculation), adjusting line 2 to 5.7 L/s and then adjusting line 3 until the total test room air flow reaches 48 L/s. Condition **2** represents the case with a low VR per occupant and a high VR per floor area. It is achieved by closing line 2 then adjusting line 4 to 47 L/s for the first hour of the test then reducing line 4 to 34 L/s with Line 3 adjusted to achieve the target total flow of 48 L/s in line 5. The initial plan was to provide the same fraction of air from the source room for both condition **1** and **2**, relative to the outdoor air VR, but the occupants themselves provided a significant amount of VOC emissions. To keep from exceeding our target VOC concentrations during condition **2**, the flow in line 2 was set to zero. The reason for using the high recirculation for the first hour of condition **2** was so the condition with low air change rate in the test room would still achieve steady state within the same time period as the high VR condition. This is described in more detail in the Results (see Figure 5 and associated text)

Table 3. Ventilation Test Conditions and Target Air Flow Settings (L/s)

Test Condition	Line 1	Line 2	Line 3	Line 4	Line 5
1	41.5	5.7	Balance	Off	48
2	41.5	off	Balance	34[1]	48
3	41.5	5.7	Balance	Off	48
4	41.5	41.5	Balance	Off	48

[1] Line 4 was set to 47 L/s during the first hour of condition **2** providing almost full recirculation so that the steady state concentration of bioeffluent and occupant based pollutants was reached over the same time period as condition **1**. This is described further in the report (see Figure 5)

Conditions **3** and **4** simulate the impact of an increase in VR per floor area with no change in VR per occupant. Condition **3** is the same as Condition **1** with high VR with respect to both occupancy and floor area**.** Condition **4** represents the case with high VR per occupant and low VR per unit floor-area. It was achieved by closing Line 4, closing the exhaust from the source room and opening Line 2 until 41.5 L/s flow is achieved then adjusting Line 3 until the total flow in Line 5 reaches 48 L/s.

The outdoor air intake (Lines 1 and 3) are from an outdoor air supply that is filtered with an efficient filter to maintain low particle concentrations and passed through activated carbon to remove ozone and other outdoor-air VOCs. Particle concentrations have not been significantly associated with the study outcomes in prior research. Ozone chemical reactions with some indoor pollutant sources or with some types of indoor chemicals can produce reaction products that may degrade PAQ and increase SBS symptoms. These processes and the potential reaction products are considered part of the building-related VOCs. Some laser printers emit ozone and most laser printers emit ultra-fine particles (UFP) (Maddalena et.al., 2011). Therefore, a laser printer was installed in the source room and programmed to print on a repeating schedule to provide relevant levels of office-related ozone and UFP.

Measuring Environmental Conditions during Testing

Ventilation Rate

Flow rates in the different duct lines connecting the rooms and supplying outdoor air, occupant air recirculation and/or air from the source room were measured continuously, logged every 30 seconds (APT, The Energy Conservatory, Minneapolis, MN) with venturi flow meters (accuracy ~5%) and used to calculate actual VRs in the test room. Because these flows are the most important variable in this study, the venturi flows were checked using a tracer gas decay method when the test room was unoccupied and a CO_2 mass balance when the test room was occupied using typical CO_2 generation rates for adult males and females performing office work.

To check flows with the tracer gas method, SF_6 was released instantaneously in the unoccupied test room and/or source room, or injected continuously at a known rate. The continuous

injections were used to investigate leakage between the adjacent rooms and mixing of the air streams while the instantaneous release was used to measure tracer gas decay curves and subsequent air change rate (h^{-1}) in each room. Miran SapphIRe® Model 250B infrared gas analyzers were used to monitor the tracer concentrations in real time. Air-exchange rates for the ventilation settings (conditions **1&3**, **2** and **4**) in each room were computed from curve fitting to the exponential decay in SF_6 concentration.

The CO_2 mass balance estimate of air change rates were conducted as described in Mudarri (1997) excluding the first hour of testing to allow the room to reach steady-state conditions. Occupancy and activity was constant during each session with the activity similar to typical office activity. As a result, CO_2 generation was assumed to be constant over the duration of each session. CO_2 generation is a function of energy expenditure and the ratio of energy expenditure for females to males given the same activity is 0.76 (Mudarri, 1997) for adults. Therefore, the total CO_2 generation rate (ER_{CO2}, L/s) for each session was estimated as

$$ER_{CO_2} = 0.005\left(\frac{L}{s}\right)\times M + 0.005\left(\frac{L}{s}\right)\times F\times 0.76 \qquad (1)$$

where 0.005(L/s) is the typical CO_2 generation rate for males during office activity, M is the number of males in the test room and F is the number of females. The average measured CO_2 concentration in the test room and an estimate of the outdoor CO_2 concentration (380 ppm) was used along with the session specific CO_2 generation rate to calculate the apparent air change rate (h^{-1}) in the test room during each session.

Volatile Organic Compounds (integrated samples)

VOCs were collected from both the supply and return line for the test room using multi-bed sorbent tubes. Thirty-minute samples were collected at a flow rate of approximately 120 mL/min using a variable speed multi-head peristaltic pump allowing for the simultaneous collection of two VOC and two aldehyde samples. Sample flow was monitored in each line at least two times during each sampling event using a Bios DryCal air flow calibrator. Samples were sealed in Teflon capped sleeves and stored on blue ice until returned to the lab and then transferred to a -20 °C freezer for storage until analysis.

Glass thermal desorption (TD) tubes (0.6 cm OD × 17.5 cm Length) contained a sorbent bed consisting of 2 parts by volume of CarboPack-B 60/80 mesh backed with 1 part CarboPack-X 60/80. The TD tubes were conditioned prior to each use by helium purge (~ 30 cc/min) for one hour at 300 °C in batches of 10 tubes. Conditioned tubes (analytical blanks) were routinely analyzed to confirm target VOCs were below method quantification limits.

VOC samples were analyzed following U.S. EPA Methods TO-17. Sorbent tubes were thermally desorbed for analysis by gas chromatography/mass spectrometry (TD-GC/MS) using a thermodesorption auto-sampler (Model TDSA2; Gerstel), a thermodesorption oven (Model TDS3, Gerstel), and a cooled injection system (Model CIS4; Gerstel). The cooled injection system is fitted with a Tenax-packed glass liner (P/N 013247-005-00; Gerstel). Desorption

temperatures of 25 °C with a 0.5-minute delay followed by a 60 °C/min ramp to 250 °C and a 4-minute hold time were used. The cryogenic trap was held at -10 °C during initial desorption/cryotrapping and then heated within 0.2 minutes to 270 °C at a rate of 12 °C/s, followed by a 3-minute hold time.

Analytes were resolved on a GC (Series 6890Plus; Agilent Technologies) equipped with a 30 meter HP-1701 14% Cyanopropyl Phenyl Methyl column (Model 19091U-233; Agilent Technologies) at an initial temperature of 1 °C for 0.5 minutes then ramped to 40 °C at 25 °C/min, to 115 °C at 3 °C/min and finally to 250 °C at 10 °C/min, holding for 10 minutes. The resolved analytes were detected using an electron impact MS system (5973; Agilent Technologies). The MS was operated in scan mode. All compounds over the MDL (< 1 to several ng) were evaluated by library search using the NIST spectral library. Multipoint calibrations were prepared from pure standards for common indoor pollutants and used to quantify target compounds. All pure standards and analytes were referenced to an internal standard (~120 ng) of 1-bromo-4-fluorobenzene. The concentration of qualitatively identified peaks was estimated based on the total-ion-current responses using toluene as a surrogate standard. Total volatile organic compound was identified as the total ion current between hexane and hexadecane and reported as a toluene equivalent concentration.

Volatile Organic Compounds (real-time measurements)

During the initial setup and calibration phase of the test facility and the first tests with occupants, a real-time TVOC analyzer (ppbRAE 3000, handheld photoionization detector) was used to confirm that the concentration of VOCs was in the expected range. The TVOC analyzer was important because is showed that the contribution of occupants to VOC concentrations during the high bioeffluent condition (Condition **2**) was relatively high. This resulted in a change to our initial plan to have a small fraction of air from the source room during condition **2**. The ppbRAE does not provide identification of VOCs and quantitative analysis could not be conducted immediately so to prevent VOC concentrations from being higher than our target range we turned off line 2 (flow from the source room) during condition **2**. The results from the real-time TVOC measurement were used to make final adjustments to the flow lines for the test conditions.

Low Molecular Weight Carbonyls

The target analytes in the aldehyde analysis included formaldehyde, acetaldehyde and acetone. Higher carbon-number aldehydes were quantified using the VOC method described above. Samples of these low molecular weight carbonyl compounds were collected and analyzed following ASTM Test Method D 5197-92 (ASTM, 1997). As with the VOCs, the air samples were drawn directly from the return and supply lines for the test room. Samples were collected on commercially available silica gel cartridges coated with 2,4-dinitrophenyl-hydrazine (XPoSure Aldehyde Sampler; Waters corporation). Samples were collected for 30 minutes at ~ 1 L/m using the variable speed multi-head peristaltic pump. Sample flow was monitored in each

DRAFT

line at least two times during each sampling event using a Bios DryCal air flow calibrator. Sample cartridges were capped and stored on blue ice or in the freezer until extraction.

Cartridges were eluted with 2 mL of high-purity acetonitrile into 2 ml volumetric flasks and the eluent was brought to a final volume of 2 ml before analysis. Extracts were analyzed by high-performance liquid chromatography (HPLC) (1200 Series; Agilent Technologies) using a C18 reverse phase column with 65:35 H2O:Acetonitrile mobile phase at 0.35 ml/minute and UV detection at 360 nm wave length. Multipoint calibrations were prepared for the target aldehydes using commercially available hydrazone derivatives of formaldehyde, acetaldehyde and acetone.

Acetic Acid

Acetic acid was collected in the source room initially to determine the need to include acetic acid in the study. Samples were collected the same way as the carbonyl samples but collected on silica gel sorbent tubes (P/N 22655; SKC) and extracted using 5 mL of 18 mOhm deionized water, filtered through a 0.22 micron membrane. Samples were collected from the source room for 60 minutes at ~ 1 Lpm using a variable speed peristaltic pump. Samples were stored in sealed plastic bags at -20°C until extraction and analysis.

Extracts were analyzed by ion chromatography (IC) (ICS 2000; Dionex) equipped with an autosampler (AS40; Dionex), hydroxide ion generator (EluGen cartridge, P/N 058900; Dionex) and a conductivity detector. Samples were separated on an AS11 column (P/N 044076; Dionex) at a flow rate of 1.0 ml/min. The column was not heated. An injection loop of 25 µL was used to inject samples. A gradient of hydroxide ions was generated starting at 0.20 mM for 2.3 min. before increasing to 15.00 mM at 12.0 min, then to 35.00 mM at 15.0 min. A multipoint calibration ranging from 0.287 mg/L (of extract) to 52.363 mg/L was prepared from a 1.000g/L acetate ion chromatography standard (P/N 13669; Fluka) and was used to quantify the instrument response.

Particulate Matter

Particle number concentrations were measured near the test room exhaust. Real-time size resolved particle counts were monitored using MetOne® Optical Particle Counter Model BT-637 in six channels: >0.3, >0.5, >0.7, >1, >2, and >5 µm. This instrument has a counting efficiency of about 50% for 0.3 µm particles, so particle counts in the first channel are uncertain. Ultrafine particle (UFP) counts were measured near the test room exhaust using a water-based condensation particle counter (TSI® WCPC). The WCPC counts particles >6 nm. The sample inlet has a cyclone with a cut-off diameter of 3 µm so sampling range is approximately 0.006 – 3.0 µm. UFP counts were recorded at one-minute time interval. The difference between the WCPC and the >0.3 µm particle number concentration from the MetOne provides a rough estimate of the ultra-fine particle number concentration.

Ozone

Concentrations of O_3 were monitored using a real-time gas analyzer (2BTech® Model 205) collected from near the test room exhaust. The gas analyzer was checked prior to use and zero-

offset of the instruments were determined in the laboratory by sampling with an O_3 scrubber attached to the sample inlet. The offset values, which range between 5 to <1 ppb, were subtracted from the data. The instrument failed during the experiment but initial results indicate that O_3 remained near background for all conditions tested.

Carbon Dioxide

CO_2 was measured using an EGM-4 non-dispersive infrared analyzer (PP Systems International Inc., Amesbury MA) in both the supply and the return line for the test room. The supply line provides information about background CO_2 while the return line provides a measure of indoor CO_2 in the test room. The EGM-4 is a high precision CO_2 analyzer with accuracy better than 1% used to record concentrations at one minute time interval. The analyzer connected to the supply line failed during the study so background (outdoor) CO_2 was not measured.

Temperature and Relative Humidity

The indoor air temperature and relative humidity were monitored at multiple locations within the test room and surrounding area using temperature/relative humidity data loggers. The data loggers also function as storage devices for sample flows and concentration measurements from other instruments. Temperature and humidity were measured with calibrated sensors and logged every 30 seconds (APT, The Energy Conservatory, Minneapolis, MN).

Measuring Human Outcomes

During each session, a web-based survey instrument (Appendix) was used to assess PAQ and intensity of SBS symptoms and a web-based simulation (Strategic Management Simulation, SMS) was used to assess decision-making performance. The schedule of activities during each session is provided in

Table 2. The first survey administered at 50 minutes includes additional questions related to medical history and demographics. The survey is computer-based and results are coded for the test condition and time point during the test. During unscheduled periods, subjects were free to read, study, or engage at their desk in any non-disruptive activity. During the lunch break, subjects left the room for one hour while the conditions in the test room were adjusted for the next session.

Questionnaire Data for PAQ and SBS symptoms

At three times during each session, after approximately 1 and 2 hours and, then at the end of the session, participants completed a short web-based survey (approximately 5 minutes or less). The surveys asked about environmental perceptions, health symptoms, and, only in the first survey that each participant completed, demographic variables and allergic health conditions. All questions provided an option of "no answer." Questions asked about:

- Acceptability of the indoor air quality: a 2-part question, with the first response a choice between acceptable or unacceptable, and then, depending on the initial choice,

a rating on a 7-point scale ranging either from "just barely acceptable" to "completely acceptable," or from "just barely unacceptable" to "completely unacceptable."

- Acceptability of odors in the room, with the same possible responses as for the question on acceptability of indoor air quality.
- Thermal comfort in the room, with seven categories of response, ranging from much too cool to much too warm.
- Current severity of four health symptoms, each on a 10-point scale, and also whether the participant had each symptom before arriving for the study. The symptoms were: dry, itching or irritated eyes; headache; unusual tiredness or fatigue; and congested nose.
- Demographic data – gender, age, smoking status, and education.
- Prior diagnosis of several common allergic conditions, and if they currently had asthma.

Simulation Measuring Decision-Making Performance

The current study used a method designed to assess complex cognitive functioning in ways more relevant to the tasks of workers in buildings than the tests of simulated office work generally used in indoor environmental studies (e.g., proof-reading text, adding numbers) (Wargocki et al. 2000). A computer-based program called the Strategic Management Simulation (SMS) test collects data on performance in decision making under different conditions. The SMS test has been used to study the impact on people's decision-making abilities of different drugs, VOCs from house painting, stress overload, head trauma, etc. (Breuer and Satish 2003; Satish et al. 2006; Satish et al. 2004; Satish et al. 2008; Swezey et al. 1998). SMS testing is available for research by contract with State University of New York Upstate Medical University, and for commercial applications via Streufert Consulting, LLC.

The SMS measures complex human behaviors required for effectiveness in many workplace settings. The system assesses both basic cognitive and behavioral responses to task demands, as well as cognitive and behavioral components commonly considered as executive functions. The system and its performance have been described in prior publications (e.g., Breuer and Satish 2003; Satish et al. 2004; Swezey et al. 1998). During the SMS, participants are exposed to diverse computer-generated situations presenting real-world equivalent simulation scenarios that are designed to match real-world day-to-day challenges. Several parallel scenarios are available, allowing retesting individuals without bias due to experience and learning effects. Participants are given instructions via text messages on a user-friendly computer interface, and respond to the messages using a drop-down menu of possible decisions. All participants receive the same quantity of information at fixed time points in simulated time, but participants have flexibility to take actions and make decisions at any time during the simulation, as in the real world. The

absence of requirements to engage in specific actions or to make decisions at specific points in time, the absence of stated demands to respond to specific information, the freedom to develop initiative, and the freedom for strategy development and decision implementation allow each participant to utilize his/her own preferred or typical action, planning, and strategic style. The SMS system generates measurement profiles that reflect the underlying decision-making capacities of the individual.

The computer calculates SMS performance measures as adjusted (linearized) raw scores, based on the actions taken by the participants, their stated future plans, their responses to incoming information, and their use of prior actions and outcomes. The validated measures of task performance vary from relatively simple competencies such as speed of response, activity, and task orientation, through intermediate level capabilities such as initiative, emergency responsiveness, and use of information, to highly complex thought and action processes such as breadth of approach to problems, planning capacity, and strategy. The primary factors and their definitions as reported for the SMS and included in the current experiment are:

- Basic Activity Level (number of actions taken, simple competency)
- Applied Activity (opportunistic actions, simple competency)
- Focused Activity (strategic actions in a narrow endeavor – simple competency)
- Task Orientation (focus on concurrent task demands – simple competency)
- Basic Initiative (development of new/creative activities – intermediate level capability)
- Information management (openness to, and search for information and ability to use information effectively – intermediate level capability)
- Breadth of Approach (flexibility in approach to the task – highly complex thought and action)
- Basic Strategy (number of strategic actions – highly complex thought and action)

The raw scores assigned for each measure are linearly related to performance, with a higher score indicating superior performance. Interpretation is based on the relationship to established standards of performance among thousands of previous SMS participants (Breuer and Streufert 1995; Satish et al. 2004; Satish et al. 2008; Streufert et al. 1988; Streufert and Streufert 1978; Streufert and Swezey 1986). Percentile ranks relative to the norms are calculated through a comparison of raw scores to the overall distribution of raw scores from a reference population of more than 20,000 U.S. adults, ages 16 to 83, who previously completed the SMS. The reference population was constructed non-randomly to be generally representative of the job distribution among the adult U.S. population, including college students, teachers, pilots, medical residents,

DRAFT

corporate executives, home-makers, and unemployed. The percentile calculations for individual participants are not further adjusted for age, gender, or education level.

Data Analysis

Environmental Data

Measured flows in ducts 1 – 5 (Figure 2) were logged continuously (30 second interval) along with CO_2, ozone, ultra-fine particle number concentration (>6 nm – 3 μm range), size resolved particle number concentration (>0.3 μm, >0.5 μm, >0.7 μm, >1.0 μm, >2.0 μm and >5.0 μm), temperature and relative humidity. Because the conditions in the test room were influenced by occupants and needed time to reach steady-state, the average and standard deviations are calculated separately for the first hour and the final three hours of each session.

Volatile organic chemical and aldehyde concentrations were measured as time-integrated samples over a specific sampling period. Aldehyde and VOC samples were collected from both the supply line and the return line for the test room during each session. The supply line provides a measure of the pollutant concentrations in the air entering the test room (including outdoor air, source room air and recirculated test room air) while the return line provides a measure of the pollutant concentration inside the test room. The VOC and aldehyde measurements were collected at the mid-point of each session for conditions **1**, **2** and **3**. Four replicate VOC measurements were collected at different times during condition **4** and reported individually and as the average (± standard deviation). Because condition **4** had no recirculation from the test room, and condition **2** had no air from the source room, a comparison of the measurements from the supply and return lines for these conditions provide an indication of the relative contribution of occupant and office related emissions for VOCs and aldehdyes.

Strategic Management Simulation Data

The SMS data reflect two diverse treatment conditions across different subjects and multiple response variables. The data provide separate results for the two different experiments (occupant VR scenario and floor-area VR scenario) and do not permit an overall analysis across all subjects and treatment conditions. Consequently, data analysis (within subjects) for each of the measures was separated, generating 32 subjects with self-pairing across treatments, i.e., 16 subjects per treatment cell with each subject tested for two different conditions. It is important to note that even with well-controlled research, data analysis for 16 subjects often does not generate statistical significance unless the differences between responses to treatment conditions are large. Results are reported on the basis of data provided under the designations listed in Table 1 and summarized as

- Occupant VR - Subject Groups 1,2,5 and 6
- Floor Area VR - Subject Groups 3,4,7 and 8

DRAFT

Raw scores and rank percentiles are reported for each of the SMS variables that were included in this research. Comparisons are made between conditions **1** and **2** and then separately for conditions **3** and **4,** with each comparison having n = 8 treatments; i.e., 16 subjects each in a within-subjects design with 15 degrees of freedom. Statistics are calculated for each group with analysis of variance (within subjects) techniques. The SMS analyst and programmer were blind to the experimental design and were only provided information as to the day and time that a given condition was used but not the actual condition.

Questionnaire Data

Data on acceptability of air quality and of odor were analyzed with dichotomous values (acceptable or unacceptable), and also with continuous values. For each question, the continuous scale used for analysis ranged from -7 to +7, with -7 to -1 indicating the range from "completely unacceptable" to "barely unacceptable," and +1 to +7 indicating the range from "barely acceptable" to "completely acceptable." There were no zero data values on these scales.

Acceptability of air quality and acceptability of odor, with dichotomous values, were compared across study conditions using a test of proportions, and then modeled using random effects logistic regression models. Continuous values of these outcomes were compared across conditions using paired (matched) t-tests, and then modeled with repeated measures linear models (with clusters of subject and time).

Data on severity of each of the four symptoms were analyzed either with dichotomous values (symptom present/not present), or with continuous values ranging from 0 to 7 (score=0 if no symptom was reported; otherwise set at the reported value from 1 to 7). Responses in which the symptom had existed previously were excluded from the analysis for that symptom. Worsening of preexisting symptoms was not determined or analyzed.

The occurrences of each type of symptom were compared as dichotomous values across study conditions using a test of proportions, and also in random effects logistic regression models. Continuous values of symptom severity were compared across conditions using paired t-tests and also (because of expected skewed distributions) the nonparametric Wilcoxon signed rank test (requiring no assumptions about distributions of the data), and then modeled with repeated measures linear models (with clusters of subject and time).

Results

Environmental conditions in experimental sessions

An overview of the complete study is provided in Table 4 showing the schedule and ventilation conditions for each time period along with observations about subject activities. The time period for the experiment was started five minutes after subjects entered the test room.

DRAFT

One subject logged off the SMS simulation before completion and a second subject did not have time to complete the simulation, but in both cases the responsible individual contacted the SMS programmer and confirmed that enough of the simulation had been completed to provide reliable results. Several subjects needed to be escorted to the restroom before completion of their session and the time was noted.

DRAFT

Table 4. Timeline of Study with Conditions, Seating Location and Notes for Each Experiment

						Seating Location[1]				
Date	Start	Stop	Day	Session	Condition	SE	SW	W	N	Notes:
4-Oct-12	9:05	9:55	Thu	AM	**1**	3	4	2	1	
	10:05	12:50	Thu	AM	**1**					
	14:05	14:55	Thu	PM	**2**					
	15:05	17:50	Thu	PM	**2**					
5-Oct-12	9:05	9:55	Fri	AM	**1**	3	1	4	2	
	10:05	12:50	Fri	AM	**1**					
	14:05	14:55	Fri	PM	**2**					
	15:05	17:50	Fri	PM	**2**					
6-Oct-12	9:05	9:55	Sat	AM	**1**	2	3	1	4	Subject 3 logged off SMS at 12:10 & went to restroom
	10:05	12:50	Sat	AM	**1**					
	14:05	14:55	Sat	PM	**4**					
	15:05	17:50	Sat	PM	**4**					
7-Oct-12	9:05	9:55	Sun	AM	**1**	4	1	2	3	
	10:05	12:50	Sun	AM	**1**					
	14:05	14:55	Sun	PM	**4**					
	15:05	17:50	Sun	PM	**4**					
11-Oct-12	9:05	9:55	Thu	AM	**2**	2	1	4	3	
	10:05	12:50	Thu	AM	**2**					Subject 4 to restroom 16:00; Subject 2 did not complete SMS; One subject completed extra survey.
	14:05	14:55	Thu	PM	**1**					
	15:05	17:50	Thu	PM	**1**					
12-Oct-12	9:05	9:55	Fri	AM	**2**	4	2	1	3	All SMS freeze at 10 minute. Re-start; Subject 3 to restroom at 12:15; Subject 3 completed extra survey ; Subject 3 to restroom at 15:25
	10:05	12:50	Fri	AM	**2**					
	14:05	14:55	Fri	PM	**1**					
	15:05	17:50	Fri	PM	**1**					
13-Oct-12	9:05	9:55	Sat	AM	**4**	4	1	2	3	Subject 3 to restroom at 12:15; Subject 1 to restroom at 16:40
	10:05	12:50	Sat	AM	**4**					
	14:05	14:55	Sat	PM	**1**					
	15:05	17:50	Sat	PM	**1**					
14-Oct-12	9:05	9:55	Sun	AM	**4**	2	3	1	4	
	10:05	12:50	Sun	AM	**4**					
	14:05	14:55	Sun	PM	**1**					
	15:05	17:50	Sun	PM	**1**					

[1] Two desks were placed along the south wall of the test room with one desk each on the north and west walls. Subjects were assigned numbers randomly and seated themselves. Seating locations are noted here.

The tracer decay test in the source room found that the outdoor air flow reading in the line 1 venturi flow meter (see Fig 2), supplying continuous outdoor air through the source room, was in

DRAFT

good agreement with the air change rate (h^{-1}) that was estimated using the tracer gas decay method where the ratio of air change rate determined with the venturi flow meter to the rate determined by tracer decay air change rate (h^{-1}) is 0.92 ± 0.02. In addition, the steady-state SF_6 experiments conducted with a continuous source of SF_6 in the source room confirmed that the venturi flow meters controlling the mixing of air from the source room to the test room (i.e., duct 2 venturi in Fig 2) are in good agreement with the tracer gas measurement. The ratio of the flows in Line 2 relative to Line 5 compared to the measured SF6 concentration ratio for the source and test room are within 6% ± 3%. It was also confirmed that leakage into the test room from the source room or from outside was below instrumental detection.

For the test room, all three air change rate (h^{-1}) estimation methods (CO_2 mass balance, tracer decay and venturi flow reading) were used for each condition and the results are shown in Figure 3. The ratio of the air change rate (h^{-1}) based on the venturi flow readings relative to the measured air change rate (h^{-1}) in the test room was 1.40 ± 0.17 and 1.45 ± 0.12 for the SF_6 tracer decay and the CO_2 mass balance, respectively under the conditions of high ventilation including condition **1**, **3** and **4**. This indicates that the venturi flow measurements of outdoor air ventilation during the experiments were biased high by a factor of 1.42 ± 0.21 (i.e., actual flows were lower than indicated by the venturi). For the low ventilation condition (**2**), the venturi and CO_2 mass balance measurements agreed while the SF_6 tracer decay still indicates a slightly lower air change rate (h^{-1}) than the venturi. The decay measurements were done when the test room was unoccupied while the CO_2 mass balance results were collected simultaneously with the venturi measurements during the actual experiments. However, the mass balance estimates are subject to uncertainty related to small differences in energy expenditure by subjects during the day (CO_2 generation rate) potentially leading to errors in the estimate of air change rate (h^{-1}) at low ventilation. Therefore, the SF6 tracer and CO_2 mass balance estimates of air change rate (h^{-1}) were combined resulting in a calibration factor for the flow venturi reading of 1.25 ± 0.28 during condition **2**.

The venturi measurements of outdoor air ventilation in the test room were adjusted according to the calibration factors described above to provide corrected (actual) flows. The target flows and actual ventilation flows during each session are summarized in **Error! Reference source not found.** for each time period. The Source to Test Room flow is represented by line 2 in the test facility schematic (Fig. 2). Recirculation refers to line 3 and Total refers to line 5. The target flow for Total was always 48.1 L/s. The flow through the source room was constant over the duration of the study at 41.5 (L/s). Ventilation flows are summarized in terms of the occupant based VR and the floor-area-based VR for each condition in

Table 5. The original plan had a small amount of source room air (2.8 L/s) transferred to the test room during the low ventilation scenario (Condition **2**) with the goal of providing the same apparent floor area based ventilation rate for both Condition **1** and **2**. However, the real time VOC measurements found that the total VOC concentration in the test room increased beyond our target concentration indicating that occupant generated VOCs could be an important

contribution to indoor pollutant levels during periods of low ventilation. To better distinguish between occupant borne VOCs and office borne VOCs, we elected to turn off the flow from the source room during Condition **2** representing complete ventilation of the floor area based emissions.

The temperature and humidity in the test room during each stage of the study are listed in Table 7. The overall average temperature and relative humidity during the full study were 22.5 °C (± 0.12) and 40.4% (± 1.0%), respectively. The temperature and RH were consistent across all conditions and within each condition as illustrated in Figure 4. The values measured over the first hour of the session differed by less than 1% from the values measured over the remaining three hours of the session. Average temperatures and RH are within 0.6% and 3%, respectively, across all conditions.

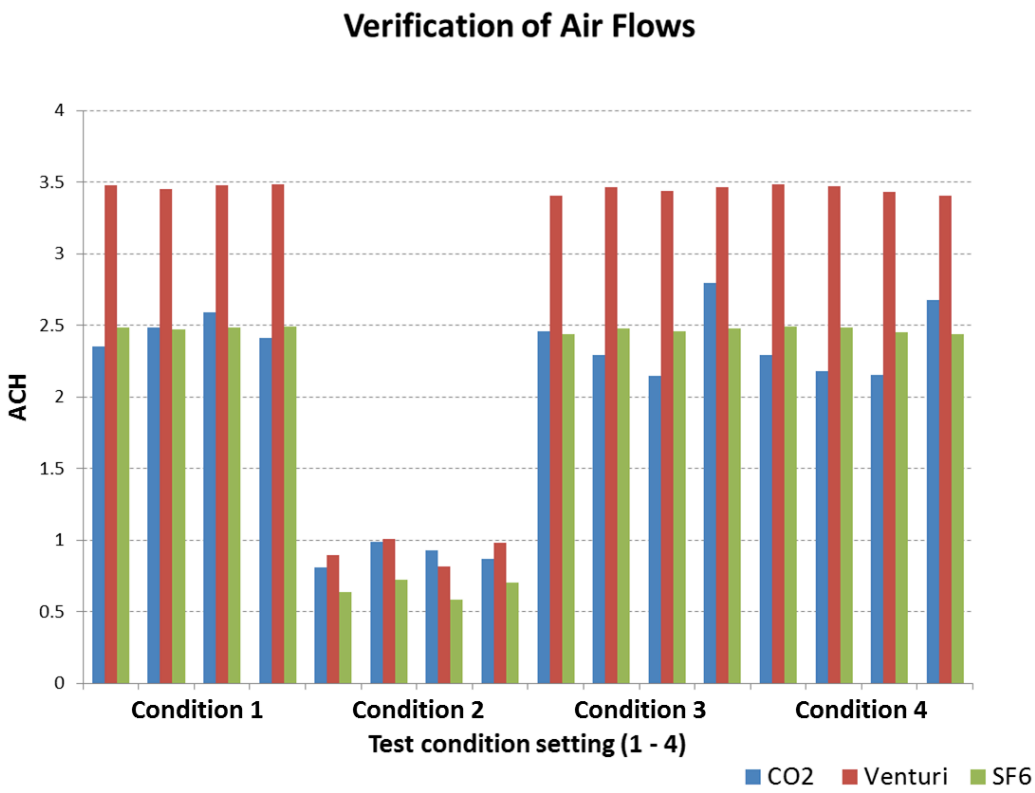

Figure 3. Quality assurance tests to confirm venturi flow readings. The air change rate (h^{-1}) estimates in the test room based on 1) the mass balance of bioeffluent (CO_2), 2) the calculated air change rate (h^{-1}) from the actual venturi readings (Venturi), and 3) the estimated air change rate (h^{-1}) from the tracer gas decay curve (SF_6) are shown for each of the four test conditions.

Table 5. Actual ventilation flows for each condition

	Occupant-based VR (L/s/person)		Floor-area-based VR (L/s/m^2)	
Condition	Average	Stdev	Average	Stdev
1	8.47	0.03	5.62	0.06
2	2.57	0.24	N/A[1]	
3	8.39	0.06	5.48	0.04
4	8.41	0.09	0.77	0.01

[1] Flow from source room to test room was turned off during Condition **2** to distinguish between office borne pollutants and occupant borne pollutants during the low ventilation test.

DRAFT

Table 6. Target and Actual Ventilation Flows (L/s)

				Source to Test Room[1]			Recirculation[2]			Total[3]	
Date	Start - Stop	Session	Cond.	Target	Ave	Stdev	Target	Ave	Stdev	Ave	Stdev
4-Oct-12	9:05-9:55	AM	**1**	5.7	5.4	0.68	off			33.8	0.3
	10:05-12:50	AM	**1**	5.7	4.0	0.01	off			33.9	0.2
	14:05-14:55	PM	**2**	off			47.2	38.1	0.5	38.9	0.5
	15:05-17:50	PM	**2**	off			34.0	29.1	1.7	39.0	0.3
5-Oct-12	9:05-9:55	AM	**1**	5.7	3.9	0.01	off			34.0	0.3
	10:05-12:50	AM	**1**	5.7	3.9	0.01	off			33.7	0.2
	14:05-14:55	PM	**2**	off			47.2	37.6	0.3	38.4	0.3
	15:05-17:50	PM	**2**	off			34.0	27.6	0.3	38.8	0.3
6-Oct-12	9:05-9:55	AM	**3**	5.7	4.0	0.02	off			33.5	0.3
	10:05-12:50	AM	**3**	5.7	4.0	0.02	off			33.2	0.2
	14:05-14:55	PM	**4**	41.5	29.2	0.03	off			33.8	0.2
	15:05-17:50	PM	**4**	41.5	29.2	0.03	off			34.0	.3
7-Oct-12	9:05-9:55	AM	**3**	5.7	4.0	0.01	off			34.4	0.3
	10:05-12:50	AM	**3**	5.7	4.0	0.01	off			33.8	0.3
	14:05-14:55	PM	**4**	41.5	29.3	0.03	off			33.9	0.2
	15:05-17:50	PM	**4**	41.5	29.3	0.03	off			33.9	0.2
11-Oct-12	9:05-9:55	AM	**2**	off			47.2	37.8	0.3	38.4	0.3
	10:05-12:50	AM	**2**	off			34.0	29.7	0.3	38.8	0.3
	14:05-14:55	PM	**1**	5.7	4.0	0.01	off			33.9	0.2
	15:05-17:50	PM	**1**	5.7	4.0	0.01	off			33.9	0.2
12-Oct-12	9:05-9:55	AM	**2**	off			47.2	37.2	1.8	38.4	0.7
	10:05-12:50	AM	**2**	off			34.0	27.4	0.3	38.3	0.3
	14:05-14:55	PM	**1**	5.7	4.0	0.01	off			34.0	0.2
	15:05-17:50	PM	**1**	5.7	4.0	0.01	off			34.0	0.2
13-Oct-12	9:05-9:55	AM	**4**	41.5	28.1	0.13	off			33.9	0.4
	10:05-12:50	AM	**4**	41.5	28.2	0.03	off			33.4	0.2
	14:05-14:55	PM	**3**	5.7	4.0	0.01	off			33.4	0.2
	15:05-17:50	PM	**3**	5.7	4.0	0.01	off			33.5	0.2
14-Oct-12	9:05-9:55	AM	**4**	41.5	28.4	0.04	off			33.3	0.3
	10:05-12:50	AM	**4**	41.5	28.4	0.03	off			33.2	0.2
	14:05-14:55	PM	**3**	5.7	4.0	0.01	off			33.8	0.2
	15:05-17:50	PM	**3**	5.7	4.0	0.01	off			33.8	0.2

[1] The target and measured flow rates (L/s) in line 2 during each session. [2] The target and measured flow rates (L/s) in line 4 during each session. [3] The total measured flow rate (L/s) in line 5 during each session where the target flow was always 48 L/s.

DRAFT

Table 7. Environmental Conditions during Testing

				Temperature (°C)				Relative Humidity (%)			
Date	Start - Stop	Session	Cond.	Ave	Stdev	Min	Max	Ave	Stdev	Min	Max
4-Oct-12	9:05-9:55	AM	**1**	22.6	0.07	22.3	22.8	43.0	0.38	42.2	43.6
	10:05-12:50	AM	**1**	22.7	0.08	22.4	22.9	41.4	0.59	40.3	42.8
	14:05-14:55	PM	**2**	22.6	0.08	22.3	22.8	39.8	0.12	39.4	40.1
	15:05-17:50	PM	**2**	22.8	0.13	22.6	23.2	39.3	0.22	38.8	39.9
5-Oct-12	9:05-9:55	AM	**1**	22.3	0.17	22.0	22.6	41.7	0.69	38.8	42.5
	10:05-12:50	AM	**1**	22.7	0.07	22.4	22.8	41.1	0.38	40.3	42.0
	14:05-14:55	PM	**2**	22.4	0.10	22.2	22.6	39.7	0.32	39.0	40.6
	15:05-17:50	PM	**2**	22.6	0.10	22.4	22.8	39.4	0.27	38.7	40.0
6-Oct-12	9:05-9:55	AM	**3**	22.4	0.19	22.0	22.6	41.5	0.44	40.4	42.3
	10:05-12:50	AM	**3**	22.8	0.20	22.4	23.3	40.3	0.71	38.9	41.7
	14:05-14:55	PM	**4**	22.5	0.08	22.3	22.7	37.9	0.55	37.0	38.8
	15:05-17:50	PM	**4**	22.4	0.10	22.1	22.6	39.2	0.30	38.6	40.0
7-Oct-12	9:05-9:55	AM	**3**	22.4	0.14	22.0	22.6	40.3	1.07	37.5	41.8
	10:05-12:50	AM	**3**	22.6	0.13	22.1	22.8	40.6	0.36	39.9	41.7
	14:05-14:55	PM	**4**	22.6	0.08	22.4	22.8	38.6	0.51	37.3	39.5
	15:05-17:50	PM	**4**	22.5	0.07	22.3	22.7	39.3	0.14	38.9	39.7
11-Oct-12	9:05-9:55	AM	**2**	22.3	0.20	21.8	22.7	40.3	1.09	36.9	41.5
	10:05-12:50	AM	**2**	22.6	0.06	22.4	22.7	40.2	0.39	39.4	41.0
	14:05-14:55	PM	**1**	22.5	0.07	22.3	22.6	40.9	0.64	38.9	41.5
	15:05-17:50	PM	**1**	22.5	0.14	22.2	22.8	40.5	0.26	39.9	41.2
12-Oct-12	9:05-9:55	AM	**2**	22.4	0.24	21.8	22.8	40.2	0.89	36.8	41.4
	10:05-12:50	AM	**2**	22.6	0.08	22.4	22.9	39.6	0.26	39.1	40.3
	14:05-14:55	PM	**1**	22.4	0.10	22.2	22.6	39.9	0.48	37.9	40.4
	15:05-17:50	PM	**1**	22.4	0.12	22.2	22.7	40.0	0.23	39.5	40.8
13-Oct-12	9:05-9:55	AM	**4**	22.4	0.21	21.8	22.9	40.0	1.19	37.1	41.7
	10:05-12:50	AM	**4**	22.5	0.06	22.3	22.7	40.7	0.34	40.0	41.3
	14:05-14:55	PM	**3**	22.6	0.07	22.4	22.7	40.8	0.39	39.9	41.5
	15:05-17:50	PM	**3**	22.5	0.13	22.1	22.7	41.0	0.28	40.3	41.6
14-Oct-12	9:05-9:55	AM	**4**	22.4	0.12	22.1	22.6	41.2	0.29	39.8	41.8
	10:05-12:50	AM	**4**	22.6	0.06	22.3	22.7	40.1	0.39	39.4	41.0
	14:05-14:55	PM	**3**	22.5	0.10	22.2	22.6	41.4	0.31	40.1	41.9
	15:05-17:50	PM	**3**	22.5	0.06	22.4	22.7	41.5	0.17	40.9	41.8

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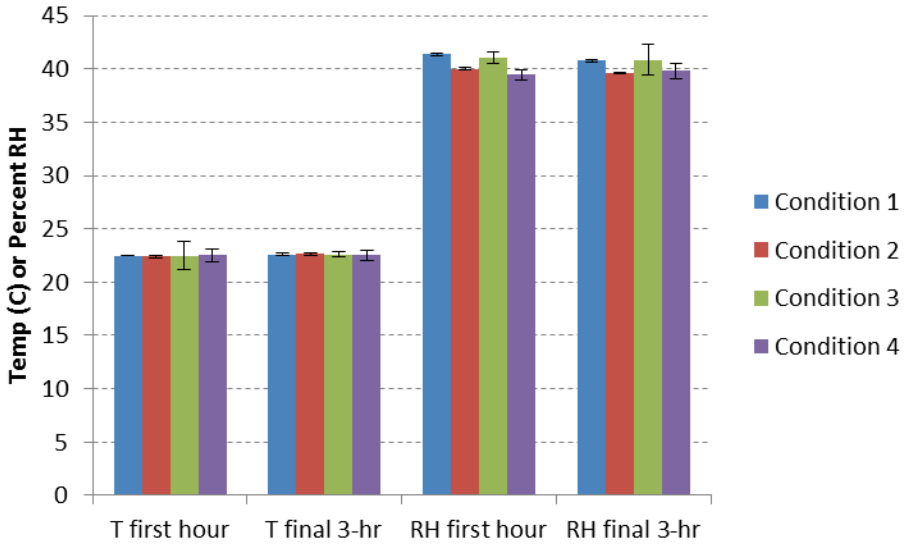

Figure 4. The average temperature and RH over the first hour and subsequent three hours for each condition in the test room are compared with the error bars indicating ± 1 standard deviation.

Although a number of different pollutants are expected to be associated with occupants, the primary marker of bioeffluents is CO_2. When a pollutant source is associated with the occupants, the test room needs time to reach a steady state concentration after the occupants (source) enter the room. The amount of time needed depends primarily on the air change rate in the space. Conditions **1**, **3** and **4** all use the same outdoor air VR resulting in the same air exchange rate so all these session reach steady-state within 1 hour of the start. In contrast, condition **2** has a much lower outdoor air VR and as a result would require almost 4 hours to reach steady state. This is illustrated in Figure 5 as the theoretical concentration profile for CO_2 in the test room assuming 4 people generating metabolic CO_2 at a constant rate of 0.005 L/s/person (Mudarri, 1997) during the test. Figure 5 shows the theoretical concentration profile during a full day where condition **2** is run during the AM session and condition **1** is run during the PM session. The problem illustrated by the panel to the left of Figure 5 is that the time to steady-state is different for the two ventilation settings by over a factor of two.

To compensate for the different VRs and still achieve steady state at over roughly the same timeframe, an artificially low VR was used during the initial hour of condition **2**. The artificially low VR was selected to bring the bioeffluent concentration to the target steady-state level without exceeding it for condition **2** within the first hour of the session. No additional source was added to the system beyond the bioeffluents from the occupants. The resulting CO_2 concentration profile including the artificially low VR over the first hour of the experiment is illustrated on the panel to the right of Figure 5.

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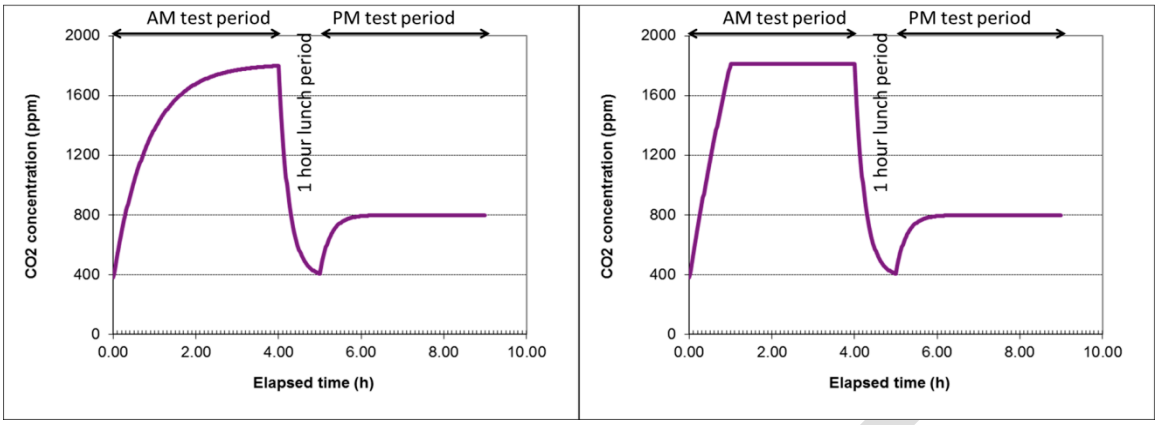

Figure 5. Illustration of the different ventilation scenarios related to occupant based pollutants showing a full day of testing with condition **2** in the AM and condition **1** in the PM. The panel to the left shows the time to steady state for CO_2 if the target (low) VR was used throughout the morning session. The panel to the right shows the concentration profile using ventilation conditions that reduce time to steady state without exceeding the target concentration.

The result is that for all test conditions (high or low ventilation settings) the steady state conditions in the test room were achieved within the first hour of testing. The actual flow settings are given in

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Table 6 and the resulting average CO_2 concentrations over each timeframe of each session are summarized in

Table 8. The average concentrations are shown in Figure 6 demonstrating that only condition **2** had elevated bioeffluents and that for the occupant-generated source required time to reach steady state in the test room.

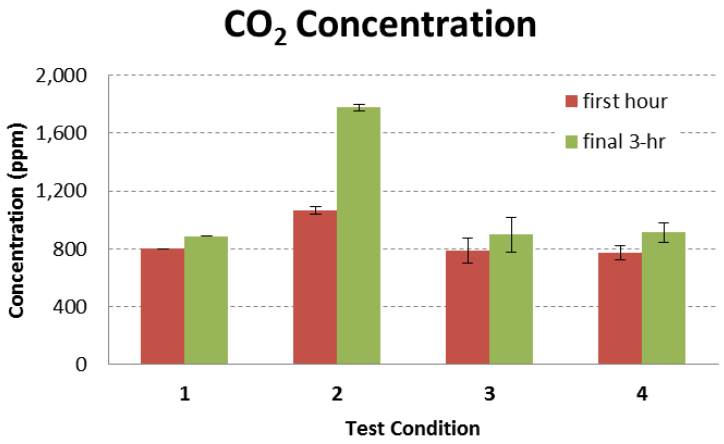

Figure 6. Comparison of average CO_2 concentration across the different conditions for the first hour and the subsequent 3 hours of each test.

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Table 8. CO_2 Concentration during each session

Date	Start - Stop	Session	Cond.	Carbon Dioxide (ppm) Ave	Stdev	Min	Max
4-Oct-12	9:05-9:55	AM	**1**	835	73	630	947
	10:05-12:50	AM	**1**	919	59	837	1113
	14:05-14:55	PM	**2**	1173	329	587	1706
	15:05-17:50	PM	**2**	1951	82	1840	2109
5-Oct-12	9:05-9:55	AM	**1**	790	106	466	913
	10:05-12:50	AM	**1**	890	39	822	985
	14:05-14:55	PM	**2**	1076	275	607	1516
	15:05-17:50	PM	**2**	1666	29	1603	1741
6-Oct-12	9:05-9:55	AM	**3**	779	80	643	893
	10:05-12:50	AM	**3**	896	27	854	980
	14:05-14:55	PM	**4**	788	101	571	915
	15:05-17:50	PM	**4**	933	15	908	991
7-Oct-12	9:05-9:55	AM	**3**	786	119	472	926
	10:05-12:50	AM	**3**	956	33	888	1067
	14:05-14:55	PM	**4**	805	73	630	926
	15:05-17:50	PM	**4**	961	20	913	1014
11-Oct-12	9:05-9:55	AM	**2**	960	289	414	1434
	10:05-12:50	AM	**2**	1744	77	1560	1854
	14:05-14:55	PM	**1**	777	81	554	876
	15:05-17:50	PM	**1**	869	13	837	911
12-Oct-12	9:05-9:55	AM	**2**	1060	328	419	1566
	10:05-12:50	AM	**2**	1744	40	1671	1816
	14:05-14:55	PM	**1**	811	86	591	910
	15:05-17:50	PM	**1**	870	17	842	949
13-Oct-12	9:05-9:55	AM	**4**	747	136	411	882
	10:05-12:50	AM	**4**	928	39	871	1027
	14:05-14:55	PM	**3**	852	65	709	932
	15:05-17:50	PM	**3**	931	19	887	1008
14-Oct-12	9:05-9:55	AM	**4**	758	56	627	841
	10:05-12:50	AM	**4**	821	22	775	883
	14:05-14:55	PM	**3**	736	70	565	824
	15:05-17:50	PM	**3**	802	27	749	858

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Detailed results for the particle number concentrations are provided in Appendix B. Sources of particles larger than 0.3 μm were not anticipated as either occupant based pollutants or as part of the source room. A typical plot of the sized resolved particle number concentrations is shown in

Figure 7. All particle size fractions follow a similar trend showing an increase in particle number concentration when the test room door was opened and occupants entered the room at 9:00 AM then another increase around 11:00AM when the responsible individual entered the test room to provide orientation and instructions for the SMS survey. The particle number concentration goes up again at the end of the session when the door is opened for occupants to exit the room. This pattern confirms that for particles in the size range greater than 300 nm, the indoor sources are limited and the particle number concentration does not vary consistently between sessions.

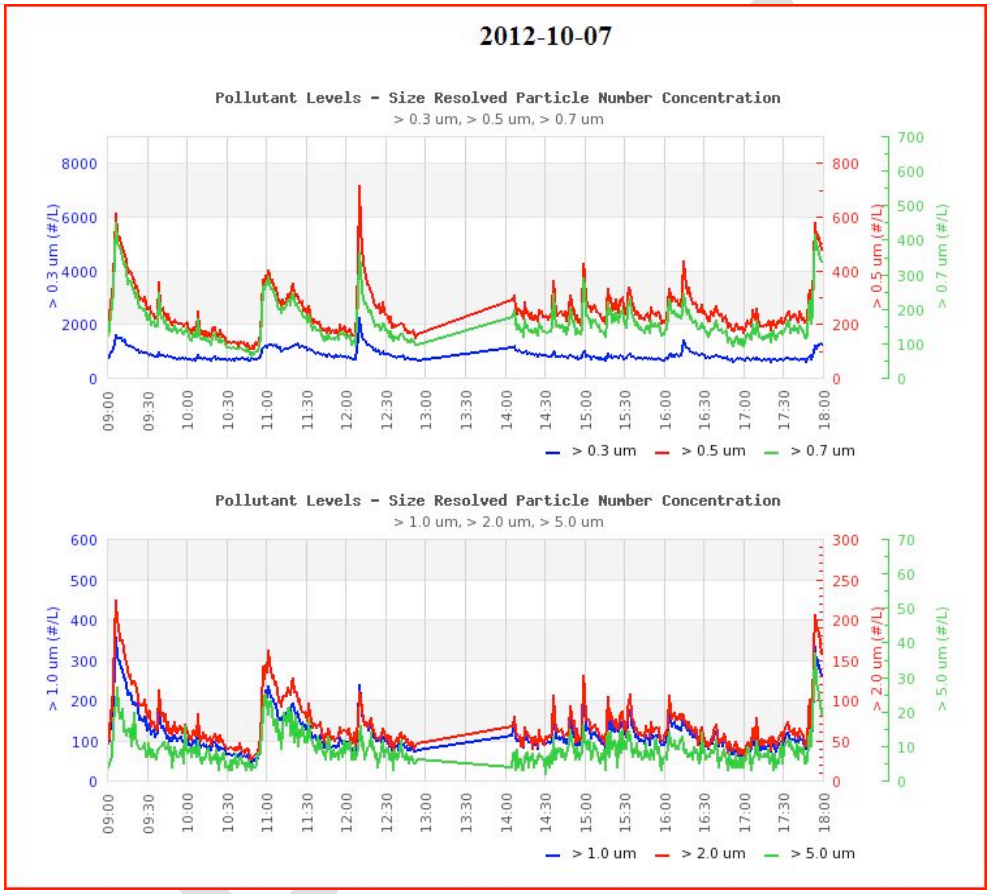

Figure 7. Sized resolved particle number concentration in the test room during occupied periods. These results were typical for all study days showing relatively low particle number concentration distributed across the six size categories.

In contrast, the ultra-fine (> 6 nm) particle number concentration were expected to be related to the office emissions. A laser printer was installed in the office and programmed to print 10 pages every 10 minutes. Laser printers are known to be a source of ultra-fine particles. A typical ultra-fine particle number concentration profile is shown in Figure 8 for the case with high VR

(floor-area and occupant-based) during the AM session and low area-based VR during the PM session. The difference between the concentration at the end of the AM session and the steady state concentration during the PM session shows the impact of the printing.

The early spike in ultra-fine particle number concentration at the start of the AM session was caused by a heat gun that was used in the test room prior to starting each session. The heat gun was used to provide a heat load to the room so that the cooling could be adjusted to compensate for the occupants prior to occupants entering the room. Unfortunately, the heat gun was later found to be a significant source of ultra-fine particles leading to the high initial loading in the test room. This issue limits the study's ability to assess human outcomes related to the ultra-fine particle sources, but the results demonstrate the opportunity for future studies to assess ultrafine particle emissions from laser printing in an office setting.

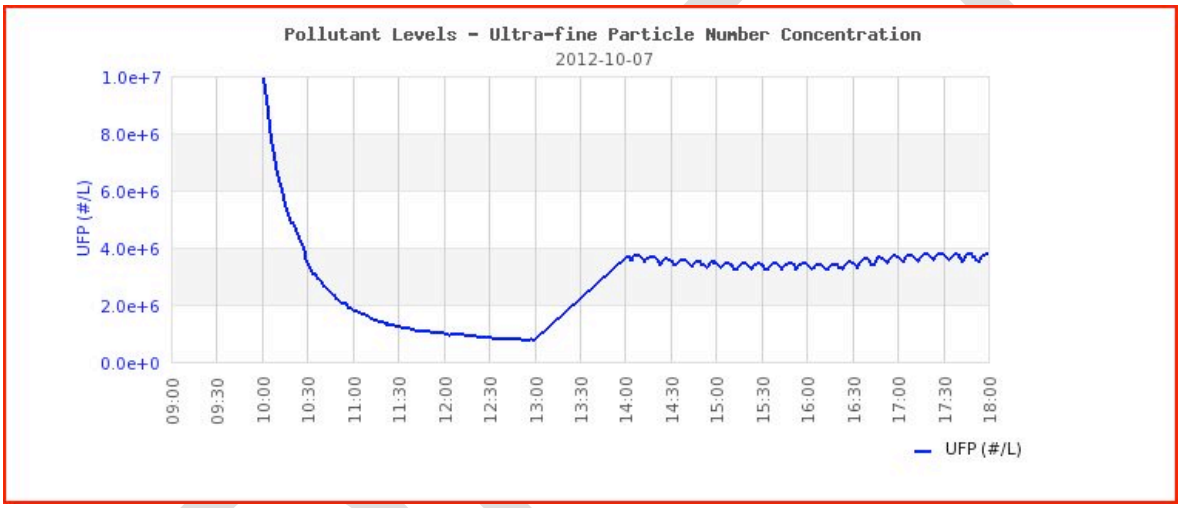

Figure 8. Ultra-fine particle number concentration profile for a day with high VR (occupant-based and area-based) in the AM and low floor-area VR during the PM session. The oscillations during the PM session clearly show the print cycle in the office space. The units were converted from the original instrument output of #/mL to #/L for comparison with the sized resolved particle number concentration data.

Table 9. Carbonyl concentration (μg/m3) during each session

Date	Start-Stop	Location	Session	Cond.	Formaldehyde	Acetaldehyde	Acetone
4-Oct-12	11:25-11:55	Supply	AM	**1**	3.96	0.93	1.69
	10:28-10:58	Return	AM	**1**	5.41	1.98	6.92
	16:29-17:13	Supply	PM	**2**	2.65	3.03	11.21
	15:26-16:27	Return	PM	**2**	5.01	5.11	17.66
5-Oct-12	11:20-11:59	Supply	AM	**1**	2.87	0.81	1.39
	10:31-11:11	Return	AM	**1**	4.01	1.65	10.30
	16:55-17:25	Supply	PM	**2**	1.79	3.47	12.04
	16:03-16:33	Return	PM	**2**	2.76	4.58	17.05
6-Oct-12	11:33-12:03	Supply	AM	**3**	3.54	1.16	1.13
	11:33-12:03	Return	AM	**3**	3.83	1.31	5.62
	16:37-17:07	Supply	PM	**4**	15.98	3.28	2.26
	16:37-17:07	Return	PM	**4**	14.77	3.60	7.47
7-Oct-12	11:29-12:02	Supply	AM	**3**	2.74	1.03	1.38
	11:29-12:02	Return	AM	**3**	4.72	1.20	8.94
	16:30-17:00	Supply	PM	**4**	15.16	3.41	2.54
	16:30-17:00	Return	PM	**4**	14.66	3.61	9.40
11-Oct-12	10:25-11:02	Supply	AM	**2**	2.60	5.77	19.38
	10:25-11:02	Return	AM	**2**	4.37	7.55	26.08
	15:42-16:15	Supply	PM	**1**	2.87	0.78	1.72
	15:42-16:15	Return	PM	**1**	4.43	1.18	9.57
12-Oct-12	10:35-11:09	Supply	AM	**2**	2.59	2.78	10.08
	10:35-11:09	Return	AM	**2**	5.18	3.64	14.24
	15:34-16:05	Supply	PM	**1**	2.64	0.62	0.89
	15:34-16:05	Return	PM	**1**	4.43	1.73	5.60
13-Oct-12	11:22-11:52	Supply	AM	**4**	14.45	2.78	2.79
	11:22-11:52	Return	AM	**4**	13.92	4.65	10.28
	15:29-15:59	Supply	PM	**3**	3.84	0.85	1.33
	15:29-15:59	Return	PM	**3**	5.69	3.88	8.68
14-Oct-12	11:30-12:00	Supply	AM	**4**	15.55	2.68	2.61
	11:30-12:00	Return	AM	**4**	14.54	3.08	7.04
	16:30-17:00	Supply	PM	**3**	3.60	0.71	1.06
	16:30-17:00	Return	PM	**3**	4.59	1.10	4.48

The measured concentrations of low molecular weight carbonyls for each session are given in

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Table 9. For the carbonyl measurements, both the supply and return lines were monitored. The supply is the air going into the test room and for conditions **1** and **3** includes a trace amount of office emission. The supply for condition **2** includes recirculated air from the test room while condition **4** includes total flow from the source room. The low molecular weight carbonyls including formaldehyde, acetaldehyde and acetone were expected to be related mostly to the source room (simulated renovation) and office furniture. This was true for formaldehyde although comparing the supply and return lines for condition **1** does show a small formaldehyde source from the occupied space where the return line concentration is slightly higher than the supply. However, most of the formaldehyde was in fact from the office as seen by comparing the supply and return lines for condition **4** (no recirculation) where the concentration in the supply line (from the source room) is consistently higher than the return line. This indicates that under very clean conditions the occupants, or their clothing, generate a small amount of formaldehyde but under normal conditions with emission from the office space, the occupied space reduces the formaldehyde concentration slightly.

The acetaldehyde concentrations were typically low in both the supply and return lines although the trend indicates a small amount of acetaldehyde produced in the occupied space. For acetone, a significant amount of the total emissions are related to the occupied space. This is illustrated by comparing the supply and return lines for condition **4** where the concentration of acetone in the return line is higher than the supply by a factor of 3.3 ± 0.5. Although acetone is commonly used in building materials, it is also known to be exhaled. In this study, the occupants appeared to be the primary source of acetone.

The total VOC concentration is defined as the total ion current for the sample chromatogram between hexane and hexadecane reported as toluene equivalents or in terms of the concentration as toluene. The results are reported here as both $\mu g/m^3$ and $ppb_{toluene}$. The TVOC in the test room is a combination of compounds emitted in the source room and compounds emitted by the occupants (and their personal items) in the test room. The measured concentrations are reported for both the supply and return lines and replicate measurements in the return line are reported for condition **4** when the VOCs were expected to be highest. Results for the VOC measurements are given in

The measured VOC concentration in the supply line for conditions **1** and **3,** with no recirculation of test room air and only a small addition from the source room, confirms that the background office related VOCs in the supply line entering the test room are low. Condition **1** and **3** also illustrate the contribution to TVOC from the occupants where the concentration in the return line from the test room is consistently higher than the supply air concentration. The contribution from occupants is further illustrated for condition **2** where there is no air from the office and the occupant based pollutants are allowed to accumulate in the test room with recirculated air. Test condition **2** was designed to explore the influence of VR on bioeffluent but it is clear that other VOCs are introduced into the space by the occupants. Figure 10 compares a chromatograms with VOCs from the occupants (measured in the return line under Condition **2**) with a chromatogram

of VOCs from the office (measured in the supply line under Condition **3**). The instrument response is proportional to concentration for a given chemical with both chromatograms on the same scale (office is inverted). The figure illustrates the complex mix of VOCs in a typical office profile with the VOCs from occupants are dominated by a smaller number of compounds that are typically associated with personal care products (siloxanes).

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Table 10. Total Volatile Organic Compound Concentration Reported as Toluene

Date	Start-Stop	Line	Session	Cond.	µg/m3	Ppb
4-Oct-12	11:59-12:33	Supply	AM	**1**	11.54	3.06
	10:28-10:58	Return	AM	**1**	56.79	15.05
	16:33-17:05	Supply	PM	**2**	36.74	9.74
	15:28-16:01	Return	PM	**2**	66.56	17.64
5-Oct-12	11:22-11:57	Supply	AM	**1**	7.07	1.87
	10:32-11:06	Return	AM	**1**	53.83	14.26
	17:55-18:25	Supply	PM	**2**	26.33	6.98
	17:03-17:33	Return	PM	**2**	39.15	10.37
6-Oct-12	11:33-12:03	Supply	AM	**3**	6.96	1.84
	11:33-12:03	Return	AM	**3**	26.70	7.07
	16:37-17:07	Supply	PM	**4**	300.03	79.51
	14:35-15:05	Return	PM	**4**	208.69	55.30
	15:29-15:59	Return	PM	**4**	203.75	53.99
	16:37-17:07	Return	PM	**4**	257.16	68.15
	17:20-17:50	Return	PM	**4**	291.77	77.32
	19:00-19:30	Return	PM1	**4**	207.27	54.93
7-Oct-12	11:29-12:02	Supply	AM	**3**	3.55	0.94
	11:24-12:02	Return	AM	**3**	19.72	5.23
	16:30-17:00	Supply	PM	**4**	247.49	65.59
	14:30-15:00	Return	PM	**4**	176.26	46.71
	15:32-16:02	Return	PM	**4**	198.26	52.54
	16:30-17:00	Return	PM	**4**	148.47	39.34
	17:20-17:50	Return	PM	**4**	261.11	69.19
11-Oct-12	10:25-11:02	Supply	AM	**2**	100.94	26.75
	10:25-11:02	Return	AM	**2**	126.72	33.58
	15:42-16:15	Supply	PM	**1**	2.92	0.77
	15:42-16:15	Return	PM	**1**	35.44	9.39
12-Oct-12	10:35-11:09	Supply	AM	**2**	216.03	57.25
	10:35-11:09	Return	AM	**2**	265.21	70.28
	15:34-16:05	Supply	PM	**1**	2.71	0.72
	15:34-16:05	Return	PM	**1**	34.29	9.09
13-Oct-12	11:22-11:52	Supply	AM	**4**	95.70	25.36
	9:33-10:03	Return	AM	**4**	120.23	31.86
	10:36-11:06	Return	AM	**4**	93.99	24.91
	11:22-11:52	Return	AM	**4**	80.94	21.45
	12:26-12:54	Return	AM	**4**	107.64	28.52
	15:29-15:59	Supply	PM	**3**	0.06	0.02
	15:29-15:59	Return	PM	**3**	38.42	10.18
14-Oct-12	11:30-12:00	Supply	AM	**4**	107.50	28.49
	9:20-9:50	Return	AM	**4**	182.06	48.25
	10:30-11:00	Return	AM	**4**	180.51	47.84
	11:30-12:00	Return	AM	**4**	203.74	53.99
	12:20-12:50	Return	AM	**4**	106.57	28.24
	16:30-17:00	Supply	PM	**3**	2.95	0.78
	16:30-17:00	Return	PM	**3**	33.05	8.76

[1] measurement in the return line collected approximately one hour after the room was empty for the day.

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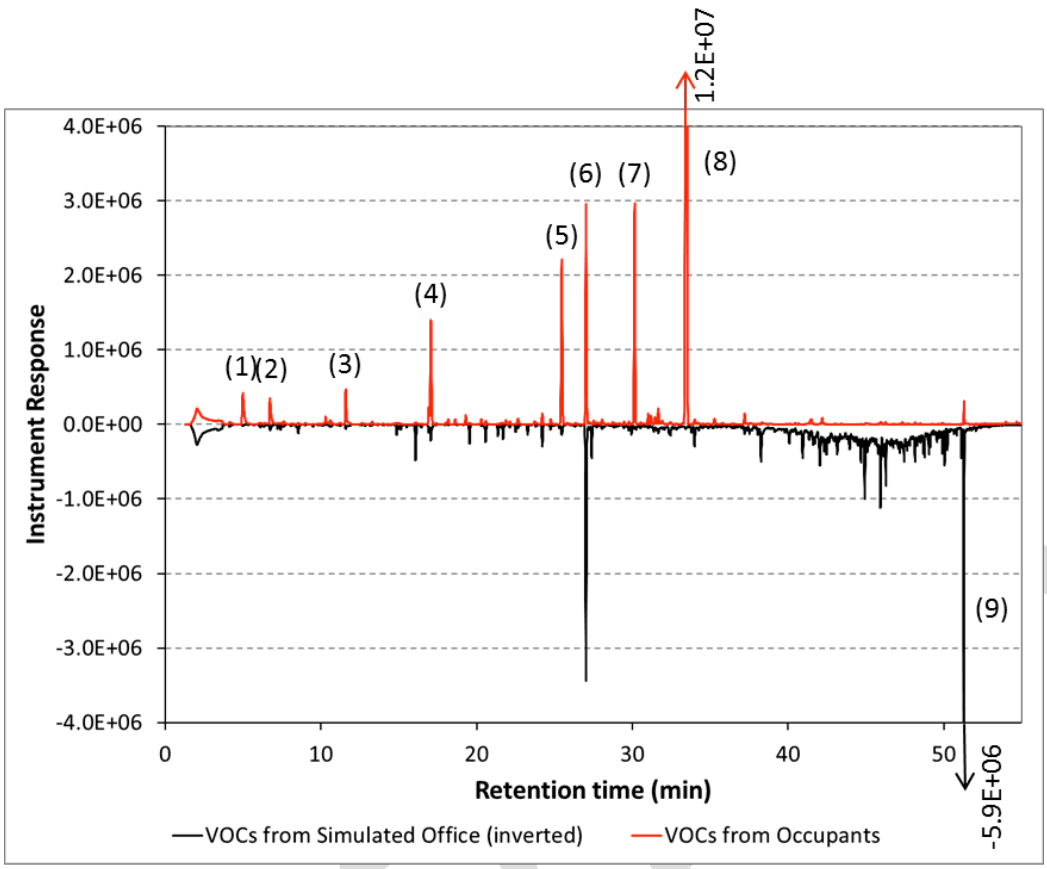

Figure 10. Comparison of the VOC profiles from occupants (top chromatogram) and the source room (inverted chromatogram). The major peaks as numbered are (1) 1,3-Pentandiene (CAS#504-60-9), (2) Acetone (67-64-1), (3) Benzene (71-43-2), (4) Hexamethyl cyclotrisiloxane (541-05-9), (5) Octamethyl cyclotetrasiloxane (556-67-2), (6) Internal Standard (bromofluorobenzene), (7) d-Limonene (5989-27-5), (8) Decamethyl cyclopentasiloxane (541-02-6), (9) 2,2,4-Trimethyl-1,3-pentane diisobutyrate (6864-50-0).

Questionnaire results

All 16 participants in each experiment completed all three surveys during both of their conditions. Two subjects completed an extra PAQ/SBS survey but the responsible individual contacted the webmaster and the survey was reset to allow the extra data to be saved. Several participants completed an additional (fourth) unsolicited survey in some sessions; these were excluded from analyses.

Questions on acceptability of air quality and odor, and on symptoms, were asked at the ends of the first and second hours in each session, and again at the end of the session (~ 4 hours). The questions asked about the subject's perceptions at that moment. In analyses for air quality and

odor, we included the responses for these questions from all three surveys completed within each condition. The analyses of symptoms excluded the reports on symptoms from the first hour of each session when conditions were stabilizing (see Figure 5 and related text). Demographic data were collected during the first survey from each person.

Demographic information about the 32 participants is provided in Table 11. Most participants (78%) were 20-29 years old, with almost all between 20 and 39 years old (91%). Slightly more females (59%) than males participated. Most (88%) had never smoked, and none were current smokers. Most were current undergraduates (41%) or college graduates (34%). The most common prior medical diagnoses reported were asthma and hay fever (19% each).

The individual responses for acceptability and symptoms questions for each subject show little notable pattern of association of any outcome with either ventilation scenario. The numbers of respondents with usable data on specific symptom severity was reduced by exclusion of subjects with specific symptoms prior to arrival on their experimental day. Among the 32 participants, the proportions with prior symptoms were 12% for headache, 19% each for eye and nasal symptoms, and 31% for fatigue.

Table 12 shows results for dichotomous (yes/no) responses on acceptability of air quality and of odor for each condition, and p-values from test of proportions. The proportions reporting unacceptable air quality and odor were lower for condition **2** (lower occupant VR) than condition **1,** contrary to hypotheses, although large p-values indicated that these difference could have been due to chance. The proportions of unacceptable air quality and odor were both higher for condition **4** (lower floor area VR) than condition **3,** which was in line with hypotheses, with the p-value for odor <0.10.

Figure C1 and Floor-area-based ventilation rate (High or Low)

Figure C1 in Appendix C show the distributions of responses on the continuous scale for acceptability and symptom questions for the comparisons of conditions **1** and **2,** and conditions **3** and **4,** respectively. No pattern of association of any response was visually evident for either pair of conditions.

Table 13 shows results for the comparisons of continuous responses on acceptability of air quality and of odor. The mean scores for acceptability of air quality and odor were both slightly lower for condition **2** than condition **1,** as hypothesized, and the paired t-test p-value for acceptability of air quality was <0.10. The mean scores for acceptability of air quality and odor were both slightly higher for condition **4** than condition **3,** which was contrary to hypotheses; although p-values were large indicating that the difference could have been by chance.

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Figure 9 shows the average TVOC for each test condition with error bars representing one standard deviation. The error bars for condition **2** illustrates the variability in occupant generated pollutants. In this case, the supply duct includes recirculated VOCs from the occupied space but no air from the source room. For condition **4**, the error bar is associated with a significant difference in TVOC concentration in the source room between week one and two of testing where the source from the source room for the first week is over double that of the second week. The reason for this large difference is unknown although it is unlikely that the emission in the source room dropped by half over one week after the materials in the office were aged for more than thirty days. The difference may have been related, at least in part, to either a change in temperature in the source room or changes in the flow through the source room.

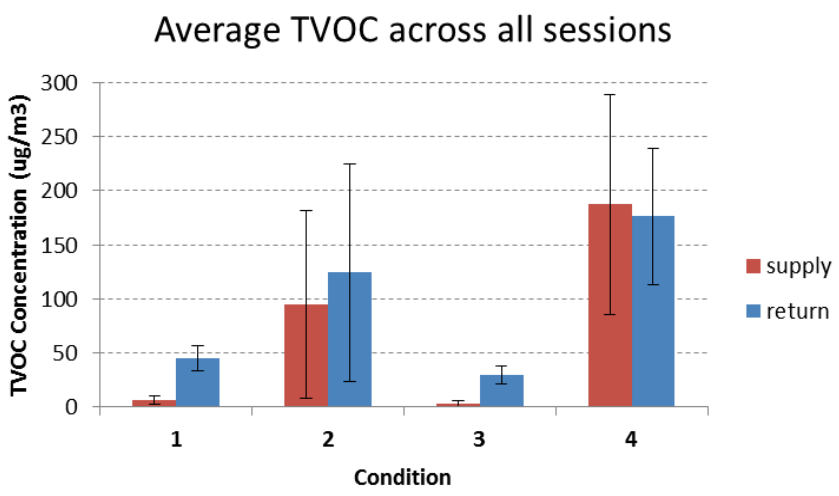

Figure 9. Comparison of the TVOC concentration during each condition averaged across all session with error bars representing one standard deviation.

The measured VOC concentration in the supply line for conditions **1** and **3**, with no recirculation of test room air and only a small addition from the source room, confirms that the background office related VOCs in the supply line entering the test room are low. Condition **1** and **3** also illustrate the contribution to TVOC from the occupants where the concentration in the return line from the test room is consistently higher than the supply air concentration. The contribution from occupants is further illustrated for condition **2** where there is no air from the office and the occupant based pollutants are allowed to accumulate in the test room with recirculated air. Test condition **2** was designed to explore the influence of VR on bioeffluent but it is clear that other VOCs are introduced into the space by the occupants. Figure 10 compares a chromatograms with

VOCs from the occupants (measured in the return line under Condition **2**) with a chromatogram of VOCs from the office (measured in the supply line under Condition **3**). The instrument response is proportional to concentration for a given chemical with both chromatograms on the same scale (office is inverted). The figure illustrates the complex mix of VOCs in a typical office profile with the VOCs from occupants are dominated by a smaller number of compounds that are typically associated with personal care products (siloxanes).

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Table 10. Total Volatile Organic Compound Concentration Reported as Toluene

Date	Start-Stop	Line	Session	Cond.	µg/m3	Ppb
4-Oct-12	11:59-12:33	Supply	AM	**1**	11.54	3.06
	10:28-10:58	Return	AM	**1**	56.79	15.05
	16:33-17:05	Supply	PM	**2**	36.74	9.74
	15:28-16:01	Return	PM	**2**	66.56	17.64
5-Oct-12	11:22-11:57	Supply	AM	**1**	7.07	1.87
	10:32-11:06	Return	AM	**1**	53.83	14.26
	17:55-18:25	Supply	PM	**2**	26.33	6.98
	17:03-17:33	Return	PM	**2**	39.15	10.37
6-Oct-12	11:33-12:03	Supply	AM	**3**	6.96	1.84
	11:33-12:03	Return	AM	**3**	26.70	7.07
	16:37-17:07	Supply	PM	**4**	300.03	79.51
	14:35-15:05	Return	PM	**4**	208.69	55.30
	15:29-15:59	Return	PM	**4**	203.75	53.99
	16:37-17:07	Return	PM	**4**	257.16	68.15
	17:20-17:50	Return	PM	**4**	291.77	77.32
	19:00-19:30	Return	PM[1]	**4**	207.27	54.93
7-Oct-12	11:29-12:02	Supply	AM	**3**	3.55	0.94
	11:24-12:02	Return	AM	**3**	19.72	5.23
	16:30-17:00	Supply	PM	**4**	247.49	65.59
	14:30-15:00	Return	PM	**4**	176.26	46.71
	15:32-16:02	Return	PM	**4**	198.26	52.54
	16:30-17:00	Return	PM	**4**	148.47	39.34
	17:20-17:50	Return	PM	**4**	261.11	69.19
11-Oct-12	10:25-11:02	Supply	AM	**2**	100.94	26.75
	10:25-11:02	Return	AM	**2**	126.72	33.58
	15:42-16:15	Supply	PM	**1**	2.92	0.77
	15:42-16:15	Return	PM	**1**	35.44	9.39
12-Oct-12	10:35-11:09	Supply	AM	**2**	216.03	57.25
	10:35-11:09	Return	AM	**2**	265.21	70.28
	15:34-16:05	Supply	PM	**1**	2.71	0.72
	15:34-16:05	Return	PM	**1**	34.29	9.09
13-Oct-12	11:22-11:52	Supply	AM	**4**	95.70	25.36
	9:33-10:03	Return	AM	**4**	120.23	31.86
	10:36-11:06	Return	AM	**4**	93.99	24.91
	11:22-11:52	Return	AM	**4**	80.94	21.45
	12:26-12:54	Return	AM	**4**	107.64	28.52
	15:29-15:59	Supply	PM	**3**	0.06	0.02
	15:29-15:59	Return	PM	**3**	38.42	10.18
14-Oct-12	11:30-12:00	Supply	AM	**4**	107.50	28.49
	9:20-9:50	Return	AM	**4**	182.06	48.25
	10:30-11:00	Return	AM	**4**	180.51	47.84
	11:30-12:00	Return	AM	**4**	203.74	53.99
	12:20-12:50	Return	AM	**4**	106.57	28.24
	16:30-17:00	Supply	PM	**3**	2.95	0.78
	16:30-17:00	Return	PM	**3**	33.05	8.76

[1] measurement in the return line collected approximately one hour after the room was empty for the day.

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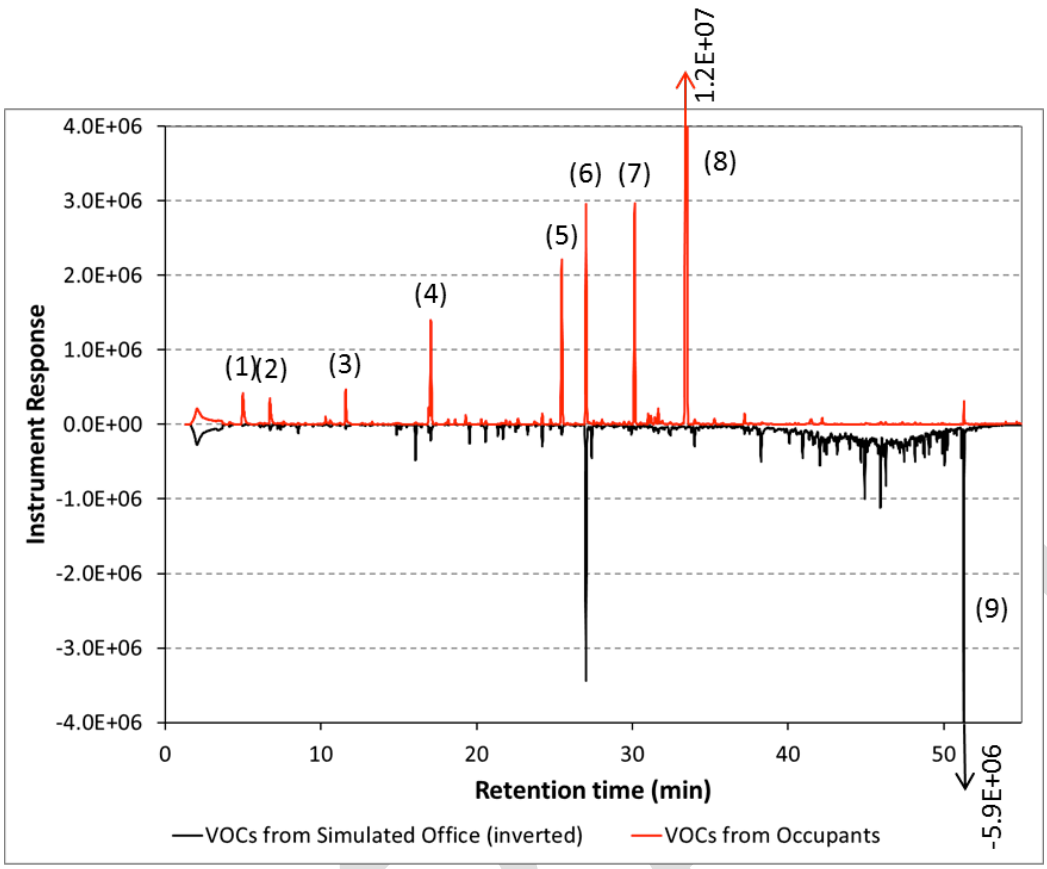

Figure 10. Comparison of the VOC profiles from occupants (top chromatogram) and the source room (inverted chromatogram). The major peaks as numbered are (1) 1,3-Pentandiene (CAS#504-60-9), (2) Acetone (67-64-1), (3) Benzene (71-43-2), (4) Hexamethyl cyclotrisiloxane (541-05-9), (5) Octamethyl cyclotetrasiloxane (556-67-2), (6) Internal Standard (bromofluorobenzene), (7) d-Limonene (5989-27-5), (8) Decamethyl cyclopentasiloxane (541-02-6), (9) 2,2,4-Trimethyl-1,3-pentane diisobutyrate (6864-50-0).

Questionnaire results

All 16 participants in each experiment completed all three surveys during both of their conditions. Two subjects completed an extra PAQ/SBS survey but the responsible individual contacted the webmaster and the survey was reset to allow the extra data to be saved. Several participants completed an additional (fourth) unsolicited survey in some sessions; these were excluded from analyses.

Questions on acceptability of air quality and odor, and on symptoms, were asked at the ends of the first and second hours in each session, and again at the end of the session (~ 4 hours). The questions asked about the subject's perceptions at that moment. In analyses for air quality and

odor, we included the responses for these questions from all three surveys completed within each condition. The analyses of symptoms excluded the reports on symptoms from the first hour of each session when conditions were stabilizing (see Figure 5 and related text). Demographic data were collected during the first survey from each person.

Demographic information about the 32 participants is provided in Table 11. Most participants (78%) were 20-29 years old, with almost all between 20 and 39 years old (91%). Slightly more females (59%) than males participated. Most (88%) had never smoked, and none were current smokers. Most were current undergraduates (41%) or college graduates (34%). The most common prior medical diagnoses reported were asthma and hay fever (19% each).

The individual responses for acceptability and symptoms questions for each subject show little notable pattern of association of any outcome with either ventilation scenario. The numbers of respondents with usable data on specific symptom severity was reduced by exclusion of subjects with specific symptoms prior to arrival on their experimental day. Among the 32 participants, the proportions with prior symptoms were 12% for headache, 19% each for eye and nasal symptoms, and 31% for fatigue.

Table 12 shows results for dichotomous (yes/no) responses on acceptability of air quality and of odor for each condition, and p-values from test of proportions. The proportions reporting unacceptable air quality and odor were lower for condition **2** (lower occupant VR) than condition **1**, contrary to hypotheses, although large p-values indicated that these difference could have been due to chance. The proportions of unacceptable air quality and odor were both higher for condition **4** (lower floor area VR) than condition **3**, which was in line with hypotheses, with the p-value for odor <0.10.

Figure C1 and Floor-area-based ventilation rate (High or Low)

Figure C1 in Appendix C show the distributions of responses on the continuous scale for acceptability and symptom questions for the comparisons of conditions **1** and **2**, and conditions **3** and **4**, respectively. No pattern of association of any response was visually evident for either pair of conditions.

Table 13 shows results for the comparisons of continuous responses on acceptability of air quality and of odor. The mean scores for acceptability of air quality and odor were both slightly lower for condition **2** than condition **1**, as hypothesized, and the paired t-test p-value for acceptability of air quality was <0.10. The mean scores for acceptability of air quality and odor were both slightly higher for condition **4** than condition **3**, which was contrary to hypotheses; although p-values were large indicating that the difference could have been by chance.

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Table 11. Descriptive information on participants

	Conditions **1&2** number	Conditions **3&4** number	Total number (%)
Gender male	7	6	13 (41%)
Age (years):			
<20	0	2	2 (6%)
20-29	11	14	25 (78%)
30-39	4	0	4 (13%)
40-49	1	0	1 (3%)
Smoking status:			
never	12	16	28 (88%)
former	4	0	4 (13%)
current	0	0	0 (0%)
Education completed:			
High school	0	3	3 (9%)
Some college	3	10	13 (41%)
College degree	8	3	11 (34%)
Graduate degree	5	0	5 (16%)
Prior medical diagnoses:			
asthma	4	2	6 (19%)
eczema	0	1	1 (3%)
hay fever	3	3	6 (19%)
dust allergy	0	1	1 (3%)
mold allergy	1	1	2 (6%)
Total number	16	16	32 (100%)

Table 12. Acceptability (dichotomous or yes/no) for air quality and odor

	Per Occupant VR test			Per Floor Area VR test		
	1 # (%)	**2** # (%)	p-value[1]	**3** # (%)	**4** # (%)	p-value
Air quality unacceptable	6 (12.5%)	3 (6.3%)	0.29	5 (10.4%)	7 (14.6%)	0.54
Odor unacceptable	5 (10.4%)	4 (8.3%)	0.73	0 (0%)	3 (6.3%)	0.08

Note – each condition had 3 eligible survey responses from 16 participants = 48 total responses, with no missing values. [1] p-values from test of proportion

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Table 14 shows the results of comparisons across the two sets of conditions for all outcomes, with dichotomous outcome values. In this table, odds ratios (ORs) >1.0 indicate increased probability of an adverse outcomes – an increased probability of unacceptability or of experiencing a symptom – and ORs <1.0 indicated decreased probability of an adverse outcome. There are no consistent patterns evident in these results, and all p-values are large. However, contrary to hypothesis, there is some tendency toward decreased probability of acceptability for air quality and odor in condition **2**.

Table 13. Acceptability (on continuous scale) of air quality and of odor

	Per Occupant VR test			Per Floor Area VR test		
	1 mean	**2** mean	p-value[1]	**3** mean	**4** mean	p-value[1]
Air quality	4.62	3.90	0.07	3.58	4.10	0.18
Odor	5.33	4.62	0.21	4.83	5.03	0.72

[1] p-values from t-test

Table 14. Association of dichotomized adverse responses from random effects logistic regression models

	Per occupant VR test Condition **2** vs. **1**		Per floor area VR test Condition **4** vs. **3**	
Acceptability and odor	OR	95% CI (p-value)	OR	95% CI (p-value)
Unacceptable air quality	0.25	0.03 – 1.98 (0.19)	1.98	0.37 – 10.64 (0.43)
Unacceptable odor	0.65	0.11 – 4.05 (0.65)	NA[1]	NA
Symptom presence[1]				
Eyes dry, itching, or irritated	0.02	0.00 – 6.3 (0.19)	2.01	0.62-6.56 (0.25)
Headache	1.24	0.50-3.06 (0.64)	0.82	0.24-2.80 (0.76)
Tiredness or fatigue	1.0	0.32-3.14 (1.0)	0.41	0.08-2.07 (0.28)
Nasal congestion	1.0	0.24-4.22 (1.0)	0.67	0.19-2.34 (0.53)

[1] Symptom presence indicates the proportion of subjects reporting a new symptom of that type, using a dichotomized outcome for each person; [2] NA – value not available representing no variation in outcome due to no responses of "unacceptable"

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Table 15. Symptom severity (continuous) using paired t-tests and the Wilcoxon signed-rank test

Symptom Severity (scale from 0 to +7)	Per occupant VR test			Per floor area VR test		
	1 mean	**2** mean	p-values: t-test[1] WSRT[2]	**3** mean	**4** mean	p-values: t-test WSRT
Eyes dry, itching, or irritated	1.53	1.40	0.52 0.61	1.58	1.46	0.80 0.92
Headache	1.70	1.60	0.84 0.93	1.40	1.07	0.45 0.47
Tiredness or fatigue	1.50	1.58	0.80 0.86	2.50	2.25	0.74 0.84
Nasal congestion	1.0	1.0	1.0 1.0	0.54	0.36	0.42 0.62

[1] t-test p-value is for two-sided test; [2] WSRT, Wilcoxon signed-rank test.

Table 15 shows comparisons across the two sets of experimental conditions for continuous responses on severity of the four symptoms that were included in the survey. There were no consistent differences in symptom severity between condition **2** and condition **1** and all p-values were large indicating no statistical difference in subject responses. Severity of symptoms was consistently slightly lower for condition **4** than condition **3**, contrary to hypotheses, although p-values were large.

Table 16 shows the results from repeated measures linear regression models of comparisons across the two sets of conditions for all acceptability and symptom outcomes, with continuous outcome values. In this table, positive linear coefficients indicate improved acceptability but more severe symptom outcomes, and negative coefficients indicate less acceptability but less severe symptom outcomes. There is no consistent pattern in acceptability outcomes for condition **2** vs. condition **1**. Condition **4**, relative to condition **3**, is associated with some decreased acceptability of both kinds, with a marginally significant decrease on the odor acceptability scale of 0.53 (p=0.06), as hypothesized. Condition **2** is associated with some decrease in all symptoms relative to condition **1**, including a significant decrease in eye symptoms (p=0.047) and a marginally significant decrease in fatigue (p=0.06), all contrary to hypotheses. For condition **4** vs. condition **3**, three of four symptoms had some increase, as hypothesized, but all four p-values were large.

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Table 16. Association of continuous outcomes from repeated measures linear regression models

	Per occupant VR test Condition **2** vs. **1**		Per floor area VR test Condition **4** vs. **3**	
Acceptability and odor[1]	Coefficient	95% CI (p-value)	Coefficient	95% CI (p-value)
Acceptable air quality	0.44	-0.24 – 1.11 (0.21)	-0.10	-0.98 – 0.77 (0.82)
Acceptable odor	-0.08	-1.07 – 0.90 (0.87)	-0.53	-1.09 – 0.02 (0.06)
Symptom severity [2]				
Eyes dry, itching, or irritated	-0.46	-0.92 – 0.005 (0.047)*	-0.17	-0.63 – 0.29 (0.48)
Headache	-0.11	-0.91 – 0.69 (0.79)	0.14	-0.56 – 0.84 (0.69)
Tiredness or fatigue	-0.58	-1.18 – 0.03 (0.06)	0.18	-0.64 – 1.0 (0.66)
Nasal congestion	-0.18	-0.53 – 0.16 (0.30)	0.25	-0.11 – 0.61 (0.18)

[1] for acceptable air quality and odor variables on a continuous scale, positive values indicate greater acceptability, a desirable outcome; [2] for symptom variables on a continuous scale, positive values indicate more severe symptoms, an undesirable outcome

SMS Decision Making Performance

All participants in each experiment completed the SMS assessment during both sessions. The raw scores for each of the SMS performance measures are plotted for each participant for the high and low per occupant ventilation scenario (Figure 11) and for the high and low per unit floor area ventilation scenario (Figure 12). For both experiments, the plots indicate a consistent reduction in cognitive function across all performance measures except Information Management. The results for Information Management were less consistent with a number of subjects showing improved performance or no change during the low ventilation condition compared to the high ventilation condition. This was the case for both the per-occupant ventilation and the per-unit floor area ventilation.

The raw scores are normalized to rank percentiles of the population and presented as the group average for each of the eight performance metrics, for the per-person ventilation scenarios in Figure 13 and the per-floor area ventilation scenario in Figure 14. Although there is considerable overlap of the error bars when the results are plotted as the average rank percentiles for the groups, the differences are highly statistically significant in the pair-wise analysis of variance, as indicated by the p-values in Table 17 for the per-person scenarios and in Table 18 for the per-floor area scenarios.

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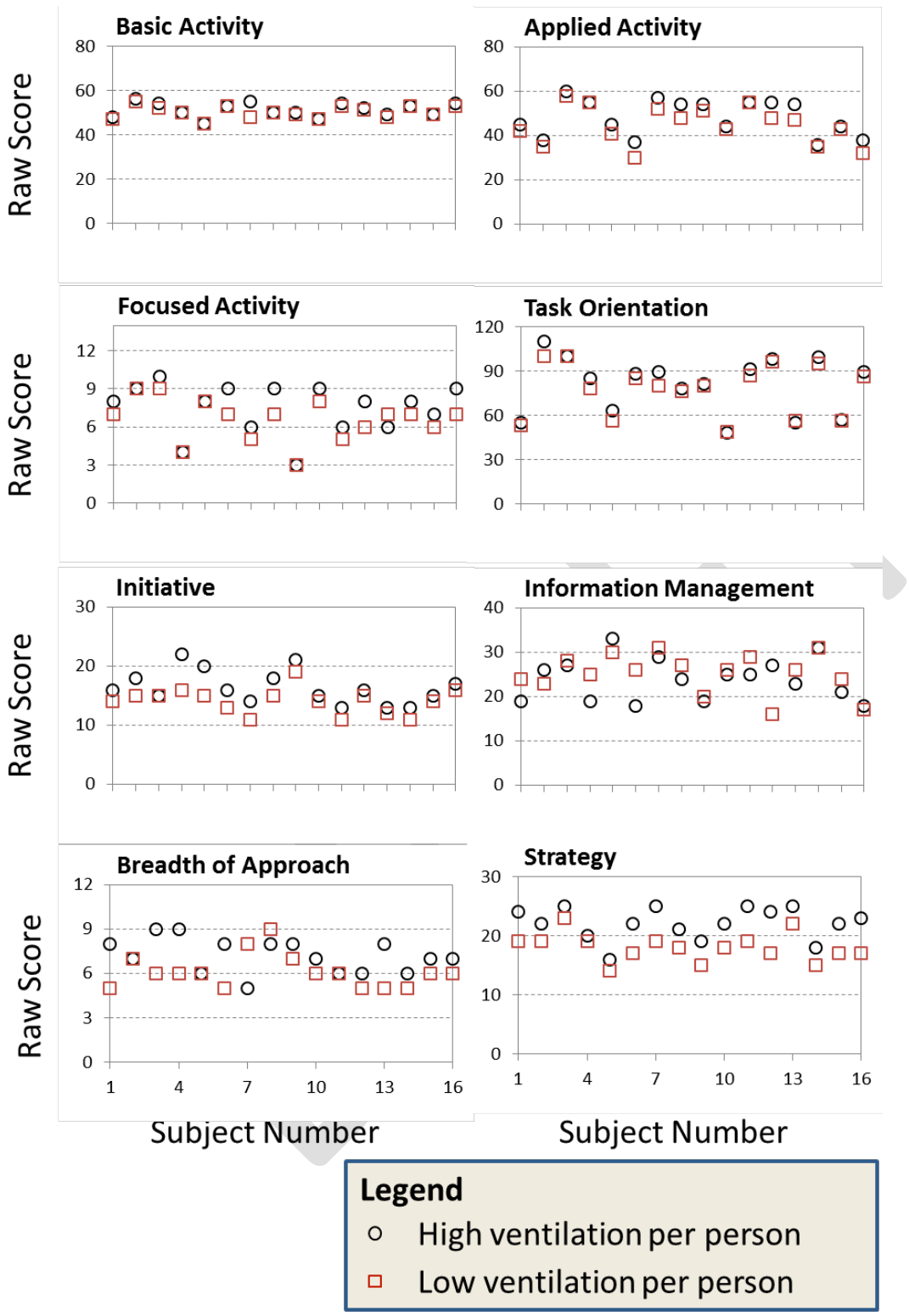

Figure 11. Raw scores reported for each individual in the test of per-occupant ventilation scenarios with the per-unit floor area ventilation maintained at a constant and elevated condition.

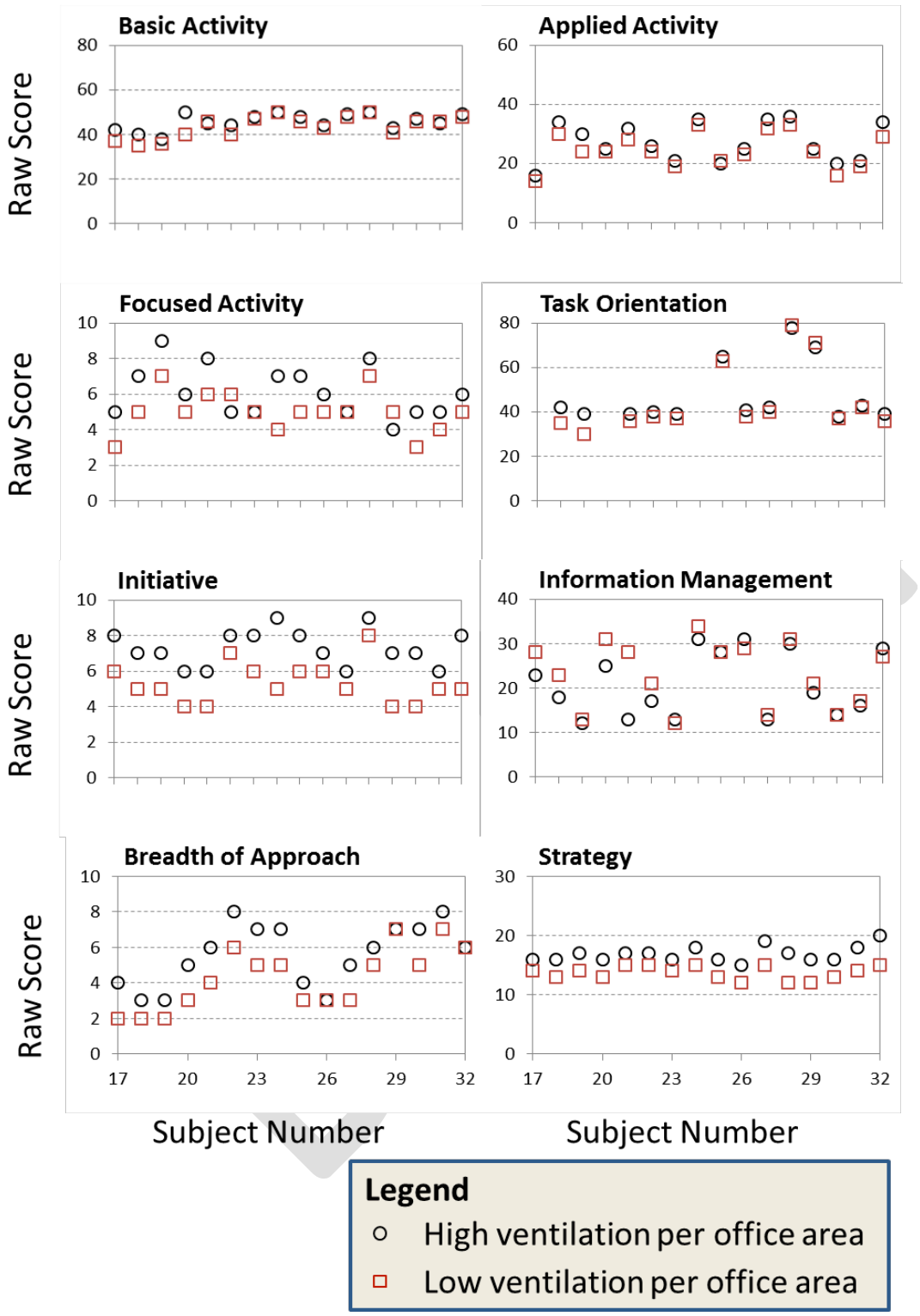

Figure 12. Raw scores reported for each subject in the test of per-unit floor area ventilation scenarios with the per-occupant ventilation maintained at a constant and elevated condition.

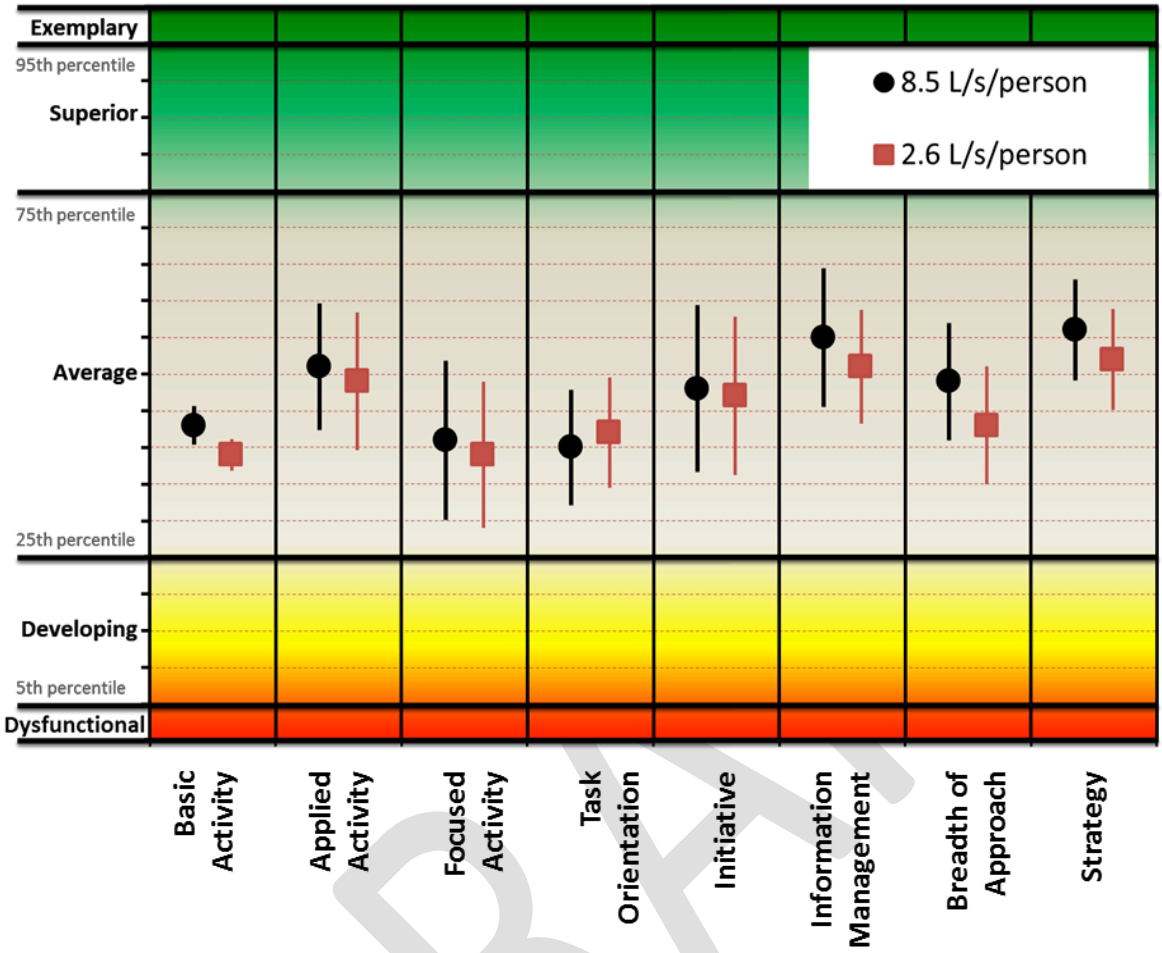

Figure 13. Average percentile ranks (± 1 standard deviation) presented for the per-person ventilation scenario.

Table 17. Pair-wise ANOVA for the per person ventilation scenarios

Performance Metric	F-Ratio	Significance (P=)
Basic activity	5.46	P = 0.034
Applied activity	30	P = 6.4 E-05
Focused activity	15.64	P = 0.001
Task orientation	15.54	P = 0.001
Initiative	32.84	P = 4.0 E-05
Information management	1.16	P = 0.299
Breadth of approach	6.51	P = 0.024
Strategy	88.14	P = 1.1 E-07

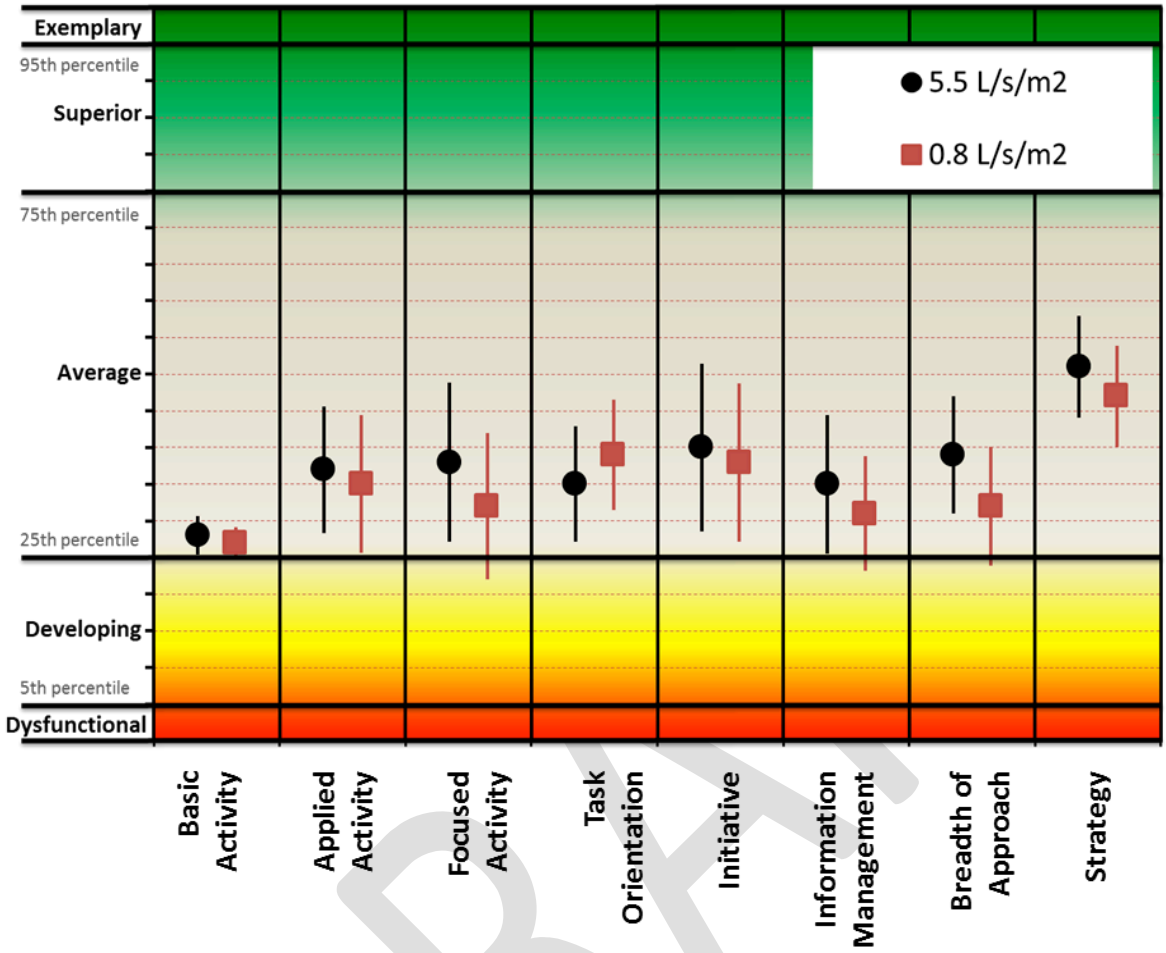

Figure 14. Average percentile ranks (± 1 standard deviation) presented for the per-unit floor area ventilation scenario.

Table 18. Pair-wise ANOVA for the floor area ventilation scenarios

Performance Metric	F -Ratio	Significance (p=)
Basic activity	8.731	P = 0.010
Applied activity	37.80	P = 1.9 E-05
Focused activity	15.380	P = 0.001
Task orientation	14.423	P = 0.002
Initiative	80.00	P = 2.1 E-07
Information management	5.528	P = 0.033
Breadth of approach	43.808	P = 8.2 E-06
Strategy	168.896	P = 1.4 E-09

The results from the current study are compared to results from Satish et.al (2012) for the decision-making performance metrics that were include in both studies. The study of Satish et.al (2012) used a constant outdoor air VR but elevated CO_2 artificially using pure CO_2 gas injected into the air supply. The current study used occupant-generated CO_2 and modified the levels by using different VRs. As a result, the data are not directly comparable, but an initial comparison is made by plotting the relative change in performance against a relative change in CO_2 concentration in the room.

The four data points used in the comparison are based on the relative change in performance as a function of the relative change in concentration. This is illustrated in Table 19 where the concentration ratios and absolute concentrations are reported along with the source. The concentration ratios highlight the fact that the results are compared as a change in decision-making performance relative to a change in concentration (or ventilation) and not in terms of the absolute concentration or absolute raw score from the SMS.

Table 19. Definition of data points (x-axis) in comparison presented in Figure 15

Concentration ratio (C_{high} / C_{low})	Concentration range (ppm)	Experiment
1.67	600 - 1000	Satish et.al.
2.00	900 - 1800	This study
2.50	1000 - 2500	Satish et.al.
4.17	600 - 2500	Satish et.al.

The change in CO_2 concentration used in the current study is similar to the smallest change condition used in Satish et.al, (2012). The starting concentration for CO_2 in the earlier study was 600 ppm CO_2 followed by a slightly elevated concentration of 1000 ppm CO_2 (Concentration ratio of 1.67). In the current study, a base concentration of 900 ppm CO_2 was used with an elevated concentration of 1800 ppm CO_2 (concentration ratio of 2.0). The earlier study also included a high concentration of 2500 ppm CO_2, providing three unique data points from Satish et.al, (2012) and one from the current study. All four points are plotted in Figure 15.

The change in performance is similar for all seven decision-making metrics used in the current study (range 0.82 – 0.98) compared to the changes associated with the lowest concentration change used in Satish et.al (2012) (range 0.82 – 0.99). Most of the factors that are included in both studies had a smaller change in cognitive function for the 900 ppm to 1800 ppm increase in biogenic CO_2 compared to the 600 ppm to 1000 ppm change in artificial CO_2. Only the Focused

Activity and Strategy had a larger reduction in cognitive function in the current study using biogenic CO_2 compared to the earlier study using artificially supplied CO_2.

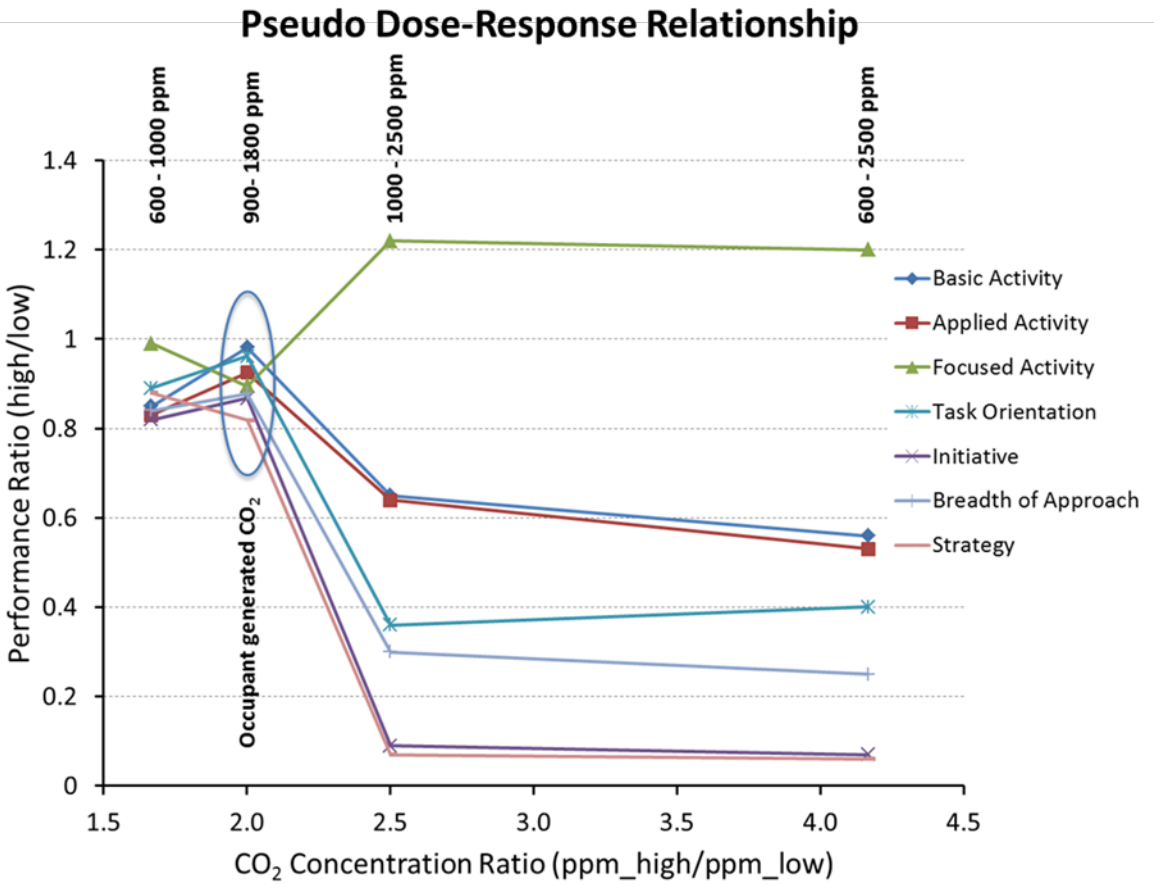

Figure 15. The performance ratio (y-axis) is calculated from the mean raw scores for each metric at each condition and the associated concentration ratio (x-axis) is calculated from the CO_2 (ppm) for each condition. The current study only used two conditions for the bioeffluent experiment resulting in one set of data point (circled in the figure). The actual high/low concentrations are listed above each set of data points.

Although all the changes in decision-making performance were statistically significant, Figure 15 shows that for relatively small changes in exposure concentration (600 ppm – 1000 ppm or 900 ppm – 1800 ppm), the effect is also moderate for all decision-making metrics. By comparison, for relatively large changes in CO_2 concentration (reductions in VR), a much larger reduction in decision-making performance is observed. This may indicate a non-linear dose response relationship between decision-making performance and VR.

Discussion

Synthesis and interpretation of findings

The hypotheses that were tested in this project were:

- Acceptability, symptoms and decision-making performance would be either the same or worse with lower per-person VR (condition **2**) compared to higher per-person VR (condition **1**), with floor-area-based VR held at a high level assuming increased exposure to human bioeffluents increased odors or irritants in the air, or in some way caused acute symptom responses;
- Acceptability, symptoms and decision-making performance would be either the same or worse with lower floor-area based VR (condition **4**) compared to the elevated office-based VR (condition **3**) with per-person VR held at a high level, to the extent that increased exposure to emissions from typical office building materials, furniture, or equipment increased odors or irritants in the air, or in some way caused acute symptom responses;
- Analyses using continuous values of the outcome variables would provide greater power and sensitivity to detect true effects for acceptability and symptoms compared to analyses using dichotomized values.

PAQ and SBS assessment

The results from the PAQ and SBS surveys produced little evidence of the hypothesized effects, of poorer acceptability or increased symptom severity with increased contaminants (lower VR), from either occupants or materials, or of any consistent effects. The only statistically significant association was the opposite of expected: in the analysis of continuous outcome values, a decrease in severity of eye symptoms with higher occupant bioeffluents, plus a marginally significant decrease in fatigue. There was only, for findings agreeing with hypotheses, a marginally significant worsening of odor acceptability, along with a small, non-significant worsening of air quality acceptability, with the increase in material emission contaminants. These findings, among many comparisons showing no associations, may simply be due to chance.

PAQ is substantially affected by odor perceptions, and perceptions of odors diminish rapidly after a change in exposure to odorous compounds. Consequently, the absence of an effect of VRs on PAQ reported after one or more hours of occupancy was not surprising. The lack of an association of VR with symptoms in this study is inconsistent with results of studies performed in actual offices. The available data from field studies were analyzed statistically by Fisk et al. (2009) and indicate a statistically significant decrease in symptoms with increased VR, with symptoms decreasing with increased VR until the VR reaches approximately 20 or 25 L/s per person. The shorter exposure period in the current study is a possible explanation. Alternately, the changes in SBS symptoms with VR may depend on sources of pollutants not present in this

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laboratory study. The small size of the laboratory studies, resulting in low statistical power, is another possible explanation.

Ventilation rate ranges used in this study were selected to be greater than the recommended minimum outdoor air VR from Title 24 and from ASHRAE 62.1 for either occupant or floor area VRs. The lack of association between VR and PAQ or SBS symptoms from this study would suggest that even lower VRs can be sustained for floor area and for occupancy without adverse impacts on PAQ and SBS symptoms. However, it would be unwise to make decisions based solely on this laboratory study, given the contradictory findings from field studies performed in office buildings.

The results using continuous values of the outcome variables were often not consistent with results using dichotomous comparisons, but again, given the small sample size and the fact that VRs were always above minimum requirements specified in Title 24 and ASHRAE 62.1, this lack of consistency may have been due to chance.

Overall, the lack of clear effects seen for PAQ and SBS symptoms may have been due to a true lack of effects at the lowest VRs used in the study, or lack of study power to detect the size effects of interest from the exposures used.

SMS Decision-Making Performance Assessment

Unlike the PAQ and SBS symptoms, the SMS tool that was used to assess decision-making performance detected a moderate but statistically significant decrease in most decision-making performance metrics as a function of decreasing either the per-person VR or the per-floor-area VR. The design carefully separated the two different ventilation scenarios. The occupant-based experiment used a 3.3-fold change in VR between the two treatments (in terms of L/s/person) while the area-based experiment used a 7.3-fold change in VR between treatments (in terms of $L/s/m^2$). The significant reductions in decision-making performance occurred without the subjects being aware of deficiencies in the VR, as shown by the lack of effects for the PAQ and SBS symptoms assessment. If substantiated, this finding would be important because it means occupants of buildings (or other enclosures) could have reduced decision-making performance because of deficiencies in VR without any perception of adverse IAQ or noticeable symptoms related to poor air quality.

To compare the importance of the two different ventilation strategies (occupant-based and area-based), the ratio of the raw decision-making performance scores for each subject was calculated for each scenario, with the average of all subjects plotted in Figure 16 (error bars indicate standard error of the mean). Each point is labeled with the specific decision-making metric and relates the effect of occupant-based VR (x-axis) to that of area-based VR (y-axis) for the conditions of this study. The results show a strong correlation between the effects of the two different ventilation scenarios across the eight decision-making metrics.

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The results in Figure 16 show a larger change in performance for the 7.3-fold change in area-based VR compared to the 3.3-fold change in occupant-based VR (slope of line = 1.6). However, assuming a linear relationship between effects and VR over the range tested, the change in performance for each metric can be normalized to the relative change in VR for each scenario and compared on a unit scale (i.e., a unit change in area-based VR compared to a unit change in occupant-based VR). The transformed data have the same correlation but the slope of the line through the data is 0.7. This implies that a unit change in occupant based VR (L/s/person) has a larger impact on decision-making performance than a unit change in area-based VR (L/s/m^2). The significance of this finding, if substantiated, would depend on the characteristics of actual buildings, primarily the building area (or more specifically, the building volume) and occupant density.

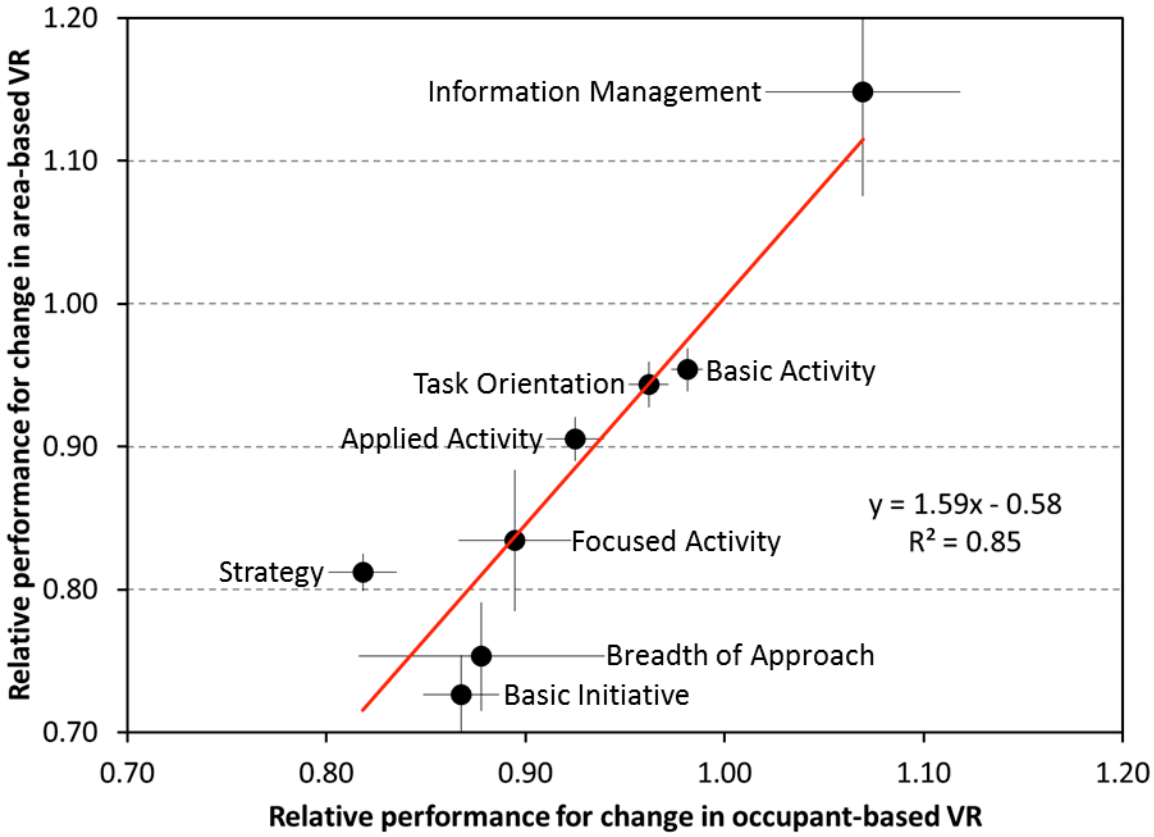

Figure 16. Comparison of the sensitivity of decision making performance metrics to changes in either occupant-based VR (x-axis) or area-based VR (y-axis).

The occupant-based VR experiments conducted on two consecutive days over two consecutive weeks (four days total) had very similar CO_2 concentration for the given treatments (Table 8). As expected, the decision-making performance metrics from week one and week two were similar

and the reduction in decision-making performance from this study agreed with earlier work using pure CO_2 (Satish et.al, 2012). However, TVOC concentrations measured during the same condition of the occupant-based VR experiments (i.e., condition **2**) differed by up to 7-fold where TVOC concentration was 10.37 ppb for condition **2** on October 5 and 70.28 ppb for the same condition on October 12. The decrease in decision-making performance on all four days of testing was similar, indicating, at least for the chemicals that differed in concentrations from week to week, that the measured chemicals did not have an impact on decision-making performance.

Likewise, the area-based VR experiments had different TVOC concentrations for the same VR conditions on consecutive weeks (Table 10) but again there was no significant difference between reductions in decision-making performance for most of the metrics for the consecutive weeks. In summary, although both the occupant-based VR and area-based VR had moderate and statistically significant impacts on decision-making performance, the study was not able to identify with certainty specific compounds in the indoor air that caused the effect.

Limitations

The power of the study was low for detecting symptom effects because of the small sample size, given the unexpected high proportion of prior specific symptoms, which excluded participants' severity data for analyses of that symptom. While other chamber studies of indoor exposures with similar sample sizes have found statistically significant effects on symptoms, the sample size in this study may have been too small for the effects of the specific exposures involved. Alternatively, it may be necessary in future studies to also assess changes in prior existing symptoms.

We performed analyses on the acceptability outcomes for air quality and odor, using continuous values, in order to use the full amount of information and achieve greater statistical power to detect effects. This required assuming that in constructing these continuous scales, the arbitrary use of 0 as the common value for separating acceptable (+1 to +7) and unacceptable (-1 to -7) scales did not introduce bias or error. We think that any bias occurring would have been to make real differences slightly more difficult to detect.

Future work

The level of sensitivity shown for a wide range of decision-making performance metrics provides an opportunity that did not previously exist for clearly delineating the dose response relationship of cognitive function and a variety of indoor environmental quality factors. A dose response assessment for outdoor air ventilation would require a study with a number of different VRs across a broad range of values.

The current study used a within-subject experimental design where both treatment levels were conducted on the same day. This limited the amount of time that a specific exposure level could be sustained. As a result, we were not able to determine if the effects seen in decision making at higher levels of exposure (lower ventilation) would be sustained over time or if subjects would

adapt to the different conditions, leading to a rebound in cognitive function. Longer duration studies are required to determine if effects are persistent. Longer studies would be significantly more difficult to balance for a number of factors, but the outcome would be extremely useful for scenarios where building occupants spend extended periods in areas with low outdoor air ventilation.

Similarly, it is not known what effect repeated exposures to low VR spaces might have. Although the current study was balanced for order of exposure (high then low or low then high), and the results did not seem to indicate a sustained effect after conditions changed, it is not clear whether exposures for a typical work day repeated for several consecutive days might reduce decision-making ability even more over time. A study designed to explore this effect would be valuable for determining minimum ventilation requirements in buildings.

Implicit in the findings that VR influences cognitive function without occupants noticing a reduction in indoor air quality is that specific compounds (or mixtures of compounds) in the indoor air are the root cause of the observed effect and VR simply modifies exposure concentrations. Research designed to identify the specific target compounds or classes of compounds that impact cognitive function could lead to other options for controlling the exposure concentrations of these compounds such as targeted source reduction or advanced air cleaning technology.

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Appendix A. On-line Survey Instrument for PAQ, SBS, Health History, and Demographic information used during HZEB Lab Study on Office Ventilation Strategies.

The different views are illustrated in order of the survey for the full survey. The follow up survey only includes the questions on "Health Symptoms" and "Satisfaction with the Current Indoor Environment".

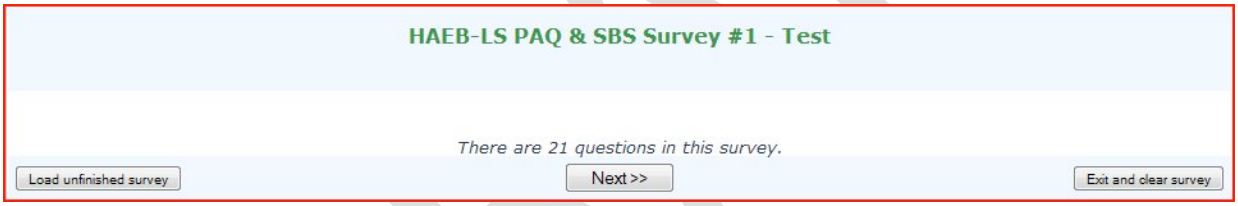
The actual Initial Survey can be viewed at

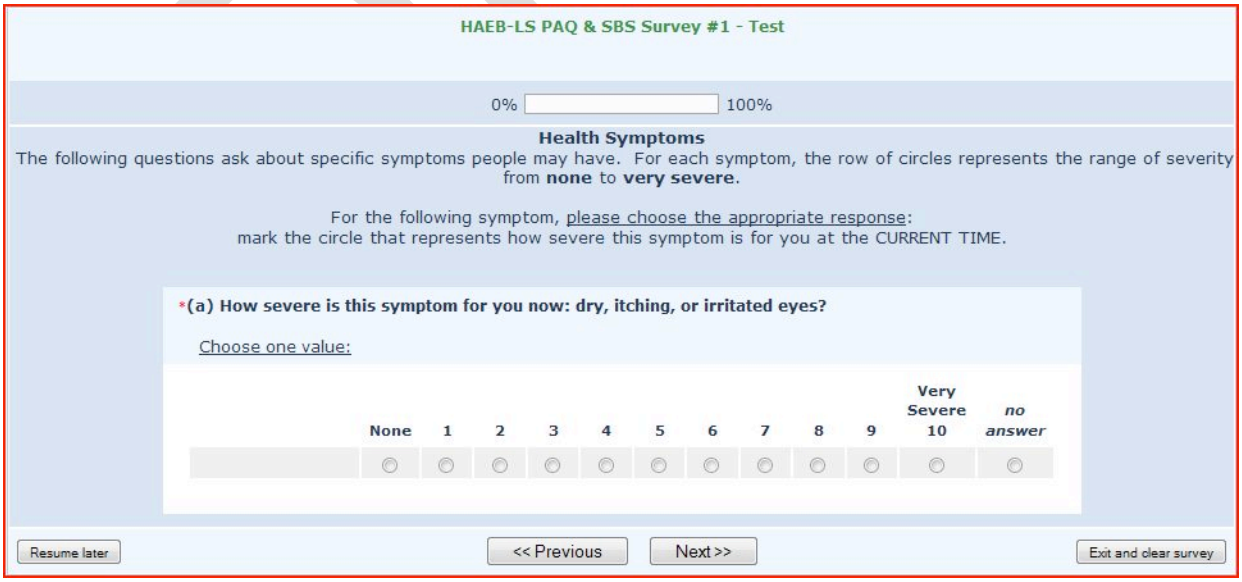
http://alpine.lbl.gov/limesurvey/index.php?sid=16546&lang=en

The follow up survey can be viewed at

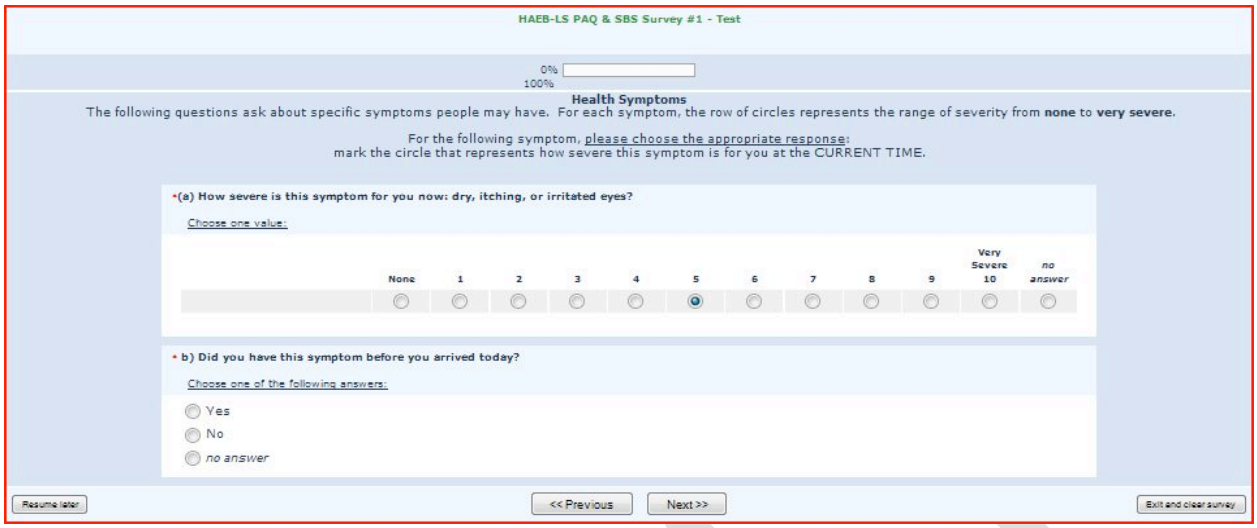
http://alpine.lbl.gov/limesurvey/index.php?sid=94223&lang=en

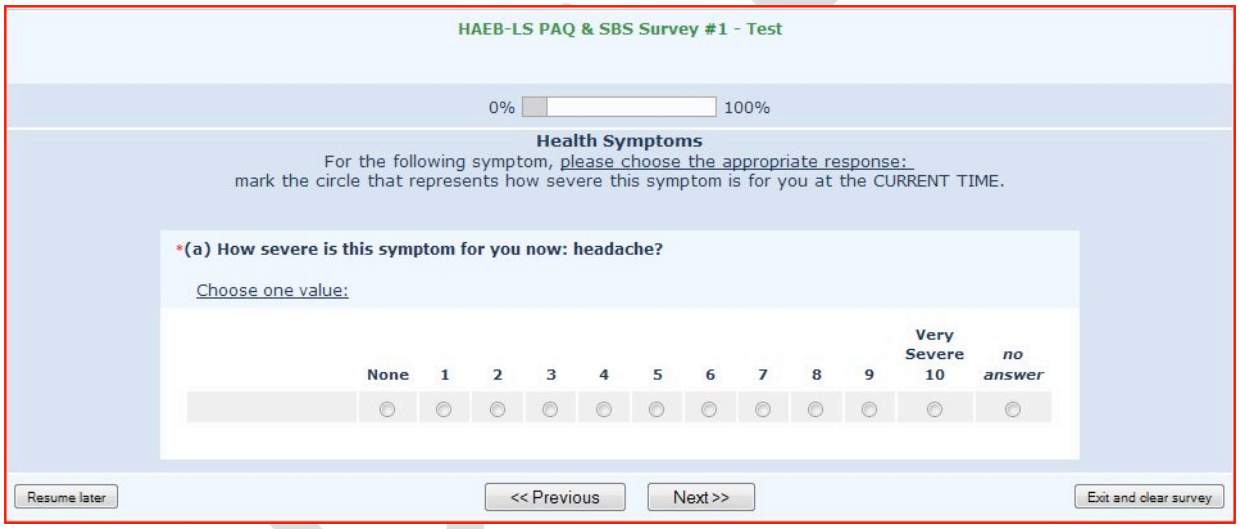
Satisfaction with the Current Indoor Environment





For the Health Symptoms view, if the subject provides an answer between 1 and 10 then the next view pops up. If "no answer" or "none" is selected then survey continues.





HAEB-LS PAQ & SBS Survey #1 - Test

0% 100%

Health Symptoms

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.

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

Choose one value:

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

Resume later << Previous Next >> Exit and clear survey

HAEB-LS PAQ & SBS Survey #1 - Test

0% 100%

Health Symptoms

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.

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

Choose one value:

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

Resume later << Previous Next >> Exit and clear survey

HAEB-LS PAQ & SBS Survey #1 - Test

0% 100%

Health History

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

Check any that apply:

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

Resume later | << Previous | Next >> | Exit and clear survey

For the Health History questions, if the subject checks any of the conditions then the following view pops up otherwise the survey continues.

HAEB-LS PAQ & SBS Survey #1 - Test

0% 100%

Health History

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

Check any that apply:

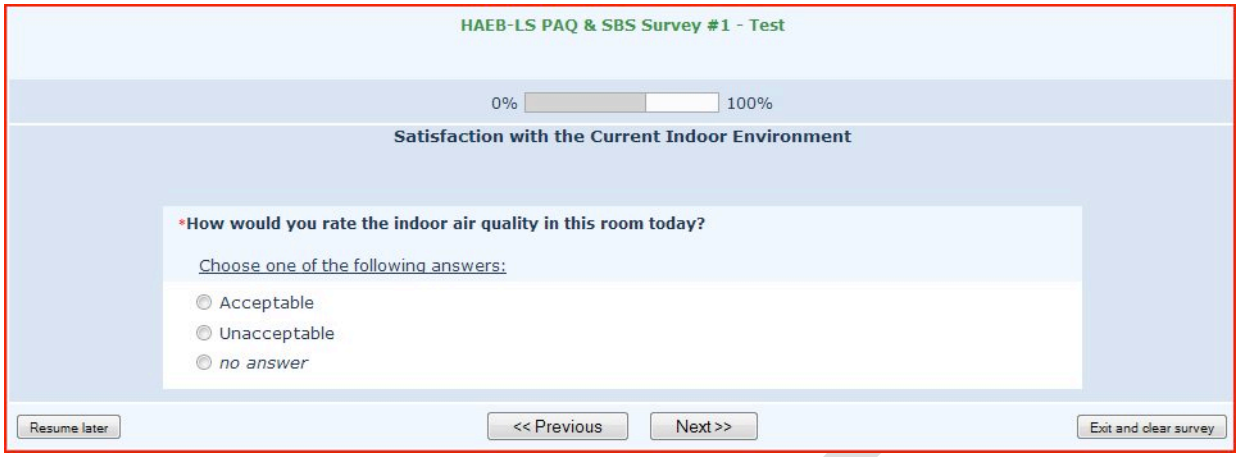
- [x] Asthma
- [ ] Eczema
- [ ] Hay fever (pollen allergy)
- [ ] Allergy to dust
- [ ] Allergy to mold
- [ ] None of the above
- [ ] *no answer*

*Do you still have asthma?

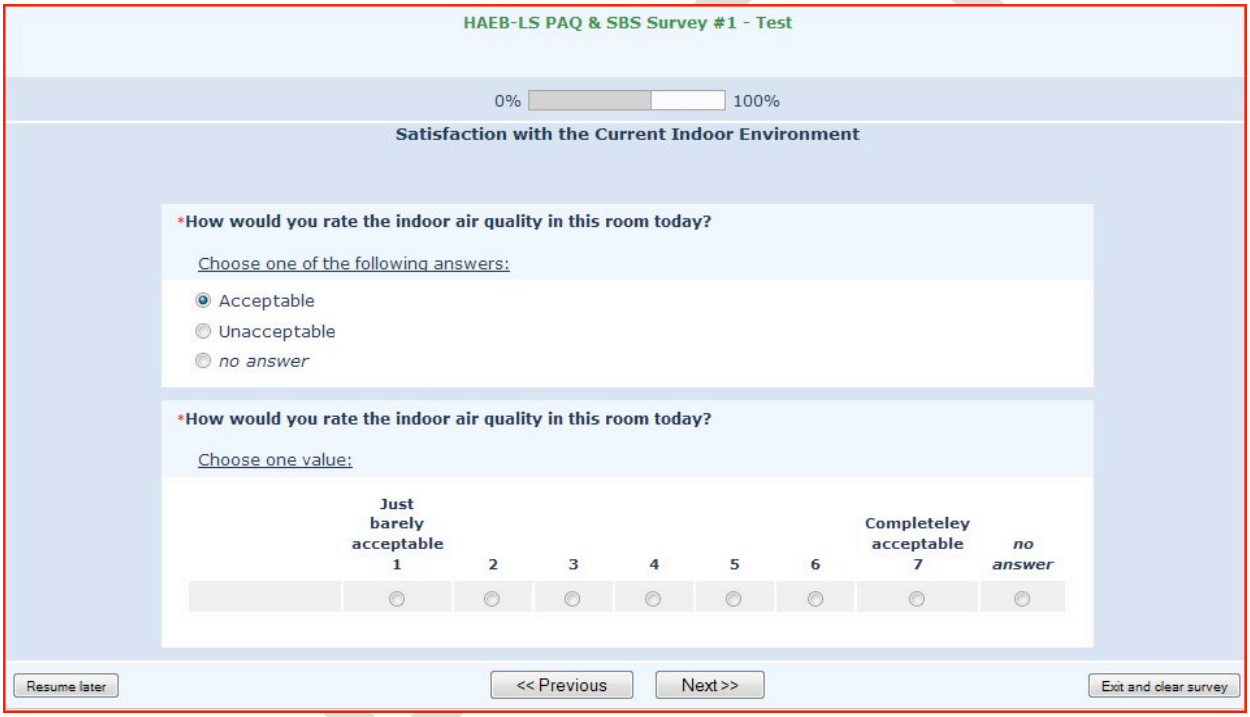
Choose one of the following answers:

- ( ) Yes
- ( ) No
- ( ) *no answer*

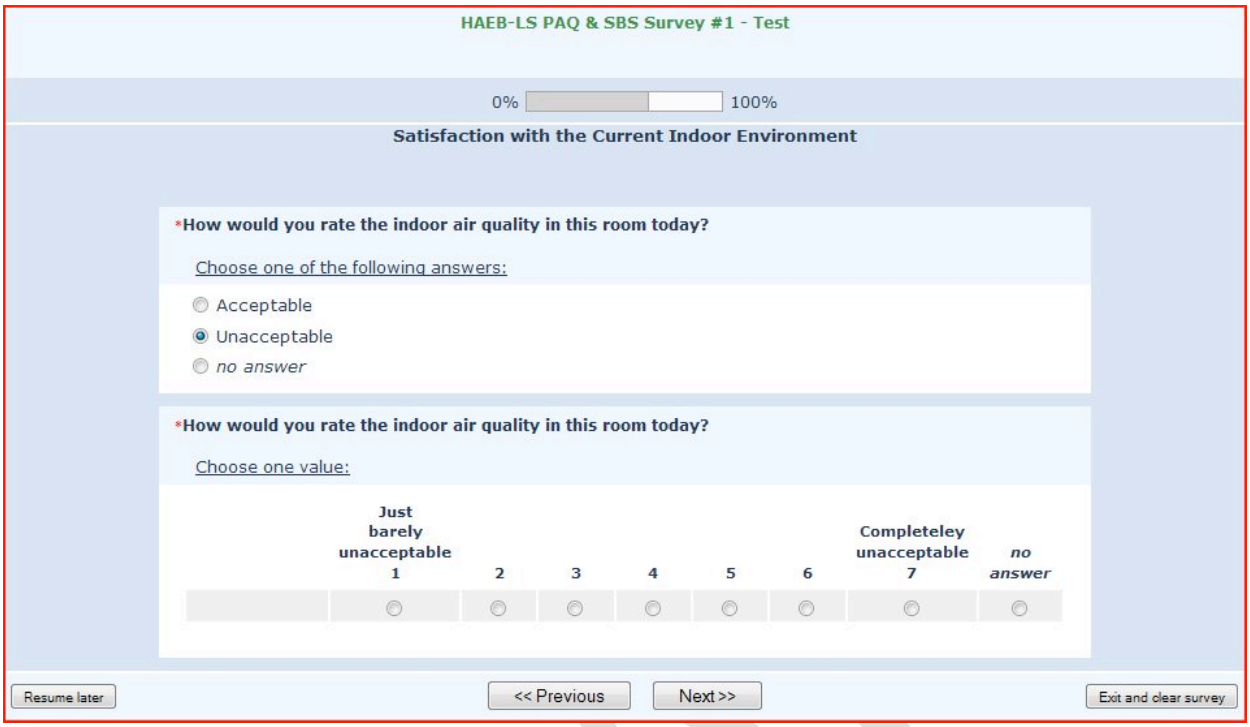
Resume later | << Previous | Next >> | Exit and clear survey

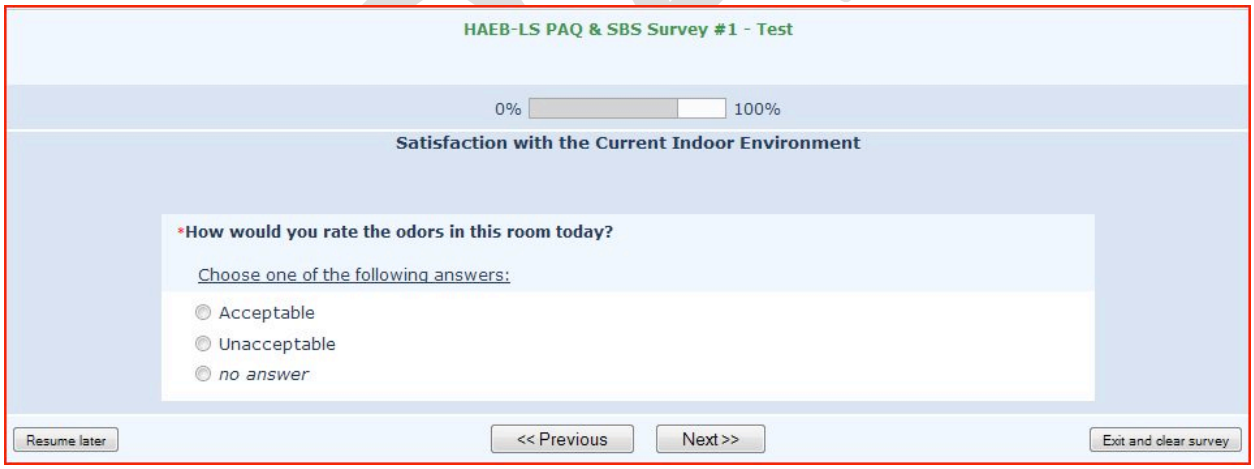


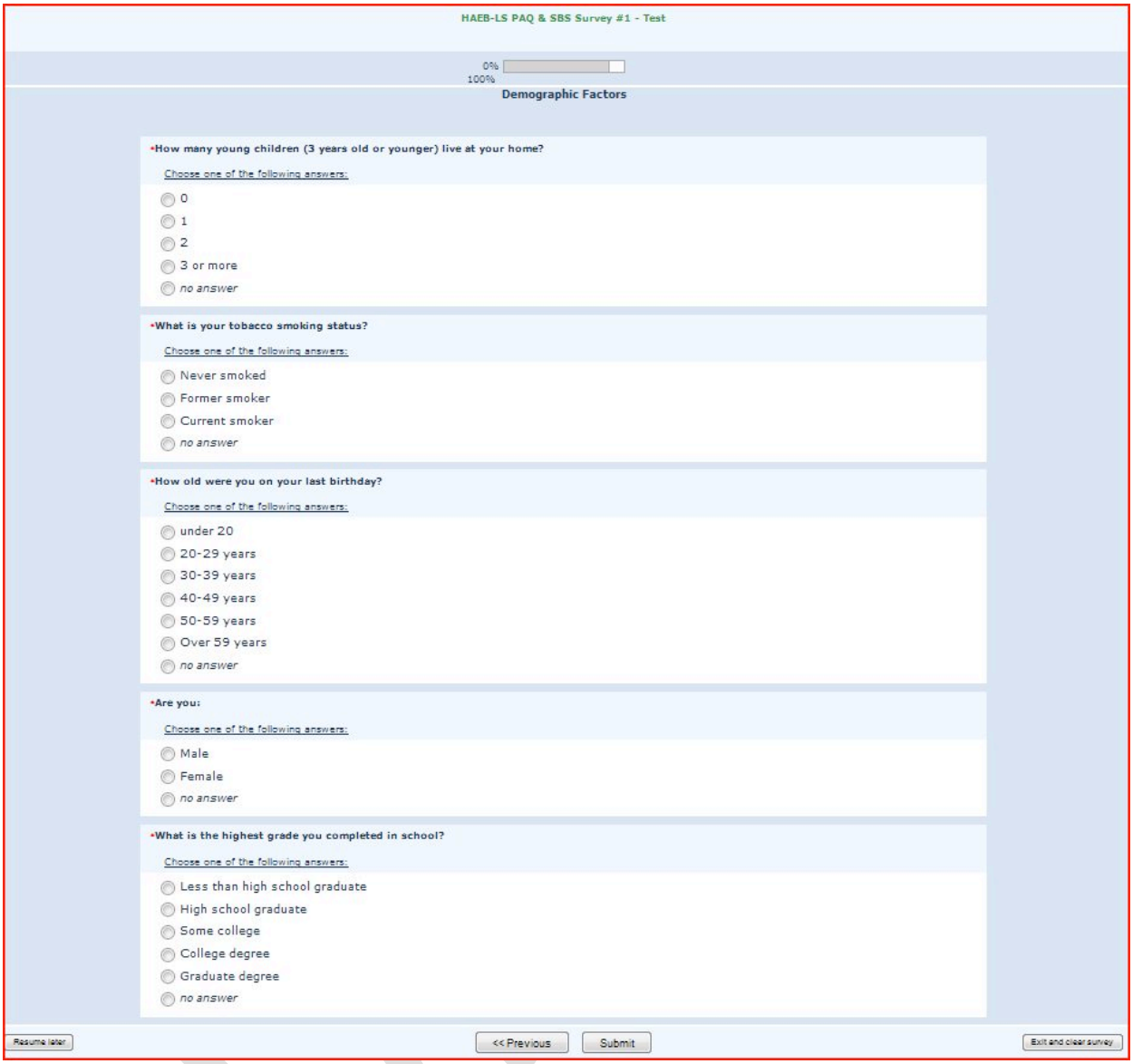
For the Satisfaction with Current Indoor Environment questions, if the subject answers Acceptable then the following view pops up otherwise survey goes to next question.

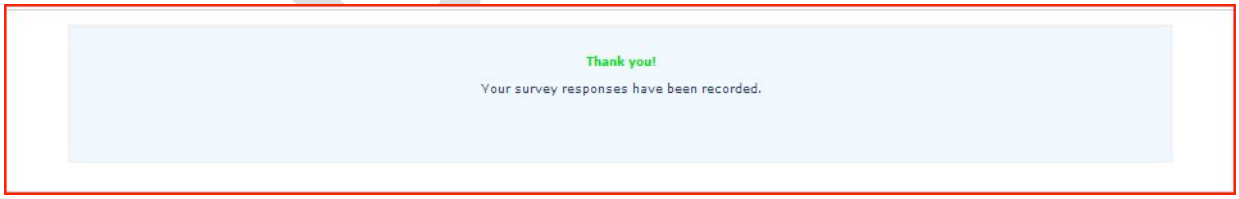


If the subject answers Unacceptable then the following view pops up, otherwise the survey continues.









The webmaster and the responsible individual supervising the study both receive automatic e-mail notification each time a subject completes a survey.

Appendix B. Particle number concentration data

Table B1. Ultra-fine Particle Number Concentration (#/mL, > 6 nm)

Date	Start - Stop	Session	Cond.	Ave	Stdev	Min	Max
4-Oct-12	9:05-9:55	AM	**1**	13332	7758	4000	29500
	10:05-12:50	AM	**1**	2021	617	1410	3390
	14:05-14:55	PM	**2**	4042	1032	2390	5730
	15:05-17:50	PM	**2**	650	336	349	1790
5-Oct-12	9:05-9:55	AM	**1**	717	64	568	795
	10:05-12:50	AM	**1**	552	233	368	1200
	14:05-14:55	PM	**2**	862	241	528	1290
	15:05-17:50	PM	**2**	200	62	135	416
6-Oct-12	9:05-9:55	AM	**3**	11598	4452	5200	19700
	10:05-12:50	AM	**3**	1178	636	694	3560
	14:05-14:55	PM	**4**	3862	260	3480	4370
	15:05-17:50	PM	**4**	3439	74	3280	3580
7-Oct-12	9:05-9:55	AM	**3**	39210	19234	13100	71400
	10:05-12:50	AM	**3**	2033	1671	789	8210
	14:05-14:55	PM	**4**	3538	117	3290	3750
	15:05-17:50	PM	**4**	3501	163	3220	3800
11-Oct-12	9:05-9:55	AM	**2**	678	126	485	919
	10:05-12:50	AM	**2**	234	53	172	417
	14:05-14:55	PM	**1**	4041	786	3050	5220
	15:05-17:50	PM	**1**	3426	577	2210	4410
12-Oct-12	9:05-9:55	AM	**2**	20752	3552	15600	25300
	10:05-12:50	AM	**2**	1057	960	222	4060
	14:05-14:55	PM	**1**	3423	158	3140	3870
	15:05-17:50	PM	**1**	3863	457	3120	4700
13-Oct-12	9:05-9:55	AM	**4**	10539	4437	5210	20600
	10:05-12:50	AM	**4**	3575	302	3170	4640
	14:05-14:55	PM	**3**	25065	15264	6790	53900
	15:05-17:50	PM	**3**	11042	6191	3330	21500
14-Oct-12	9:05-9:55	AM	**4**	5783	1613	3930	9460
	10:05-12:50	AM	**4**	3368	107	3120	3730
	14:05-14:55	PM	**3**	449	162	273	799
	15:05-17:50	PM	**3**	1224	528	316	2120

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Table B2. Particle Number Concentration (#/L, >5.0 μm)

Date	Start - Stop	Session	Cond.	Ave	Stdev	Min	Max
4-Oct-12	9:05-9:55	AM	**1**	15.6	9.6	4	41
	10:05-12:50	AM	**1**	13.8	6.6	6	38
	14:05-14:55	PM	**2**	11.9	4.7	6	27
	15:05-17:50	PM	**2**	13.1	6.6	4	61
5-Oct-12	9:05-9:55	AM	**1**	27.3	14.0	10	66
	10:05-12:50	AM	**1**	9.8	5.9	1	27
	14:05-14:55	PM	**2**	9.8	2.4	6	16
	15:05-17:50	PM	**2**	8.2	3.2	3	21
6-Oct-12	9:05-9:55	AM	**3**	10.8	3.7	6	24
	10:05-12:50	AM	**3**	9.9	4.6	2	25
	14:05-14:55	PM	**4**	6.0	2.7	2	20
	15:05-17:50	PM	**4**	7.6	2.7	2	16
7-Oct-12	9:05-9:55	AM	**3**	11.7	5.0	4	27
	10:05-12:50	AM	**3**	9.6	4.8	3	25
	14:05-14:55	PM	**4**	7.0	2.5	2	15
	15:05-17:50	PM	**4**	8.1	2.6	3	15
11-Oct-12	9:05-9:55	AM	**2**	9.6	5.5	0	23
	10:05-12:50	AM	**2**	7.0	4.2	2	22
	14:05-14:55	PM	**1**	5.6	4.4	1	22
	15:05-17:50	PM	**1**	3.5	2.5	0	15
12-Oct-12	9:05-9:55	AM	**2**	14.7	4.4	4	24
	10:05-12:50	AM	**2**	10.0	4.1	3	25
	14:05-14:55	PM	**1**	6.7	2.2	2	14
	15:05-17:50	PM	**1**	4.3	1.9	1	11
13-Oct-12	9:05-9:55	AM	**4**	22.3	8.1	6	45
	10:05-12:50	AM	**4**	18.3	10.7	4	62
	14:05-14:55	PM	**3**	13.5	3.9	6	21
	15:05-17:50	PM	**3**	15.4	8.4	4	42
14-Oct-12	9:05-9:55	AM	**4**	11.1	5.2	4	25
	10:05-12:50	AM	**4**	4.4	2.4	1	13
	14:05-14:55	PM	**3**	3.6	1.5	1	9
	15:05-17:50	PM	**3**	3.1	1.6	0	9

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Table B3. Particle Number Concentration (#/L, >2.0 μm)

Date	Start - Stop	Session	Cond.	Ave	Stdev	Min	Max
4-Oct-12	9:05-9:55	AM	**1**	126.2	66.4	51	281
	10:05-12:50	AM	**1**	92.6	37.8	38	209
	14:05-14:55	PM	**2**	144.0	31.8	98	250
	15:05-17:50	PM	**2**	116.3	38.3	76	419
5-Oct-12	9:05-9:55	AM	**1**	307.1	158.5	111	717
	10:05-12:50	AM	**1**	67.8	35.3	15	173
	14:05-14:55	PM	**2**	86.8	8.7	69	116
	15:05-17:50	PM	**2**	64.5	18.8	37	149
6-Oct-12	9:05-9:55	AM	**3**	81.2	25.0	54	159
	10:05-12:50	AM	**3**	66.9	28.5	34	150
	14:05-14:55	PM	**4**	49.4	11.4	34	77
	15:05-17:50	PM	**4**	51.3	15.6	30	108
7-Oct-12	9:05-9:55	AM	**3**	105.9	43.3	57	224
	10:05-12:50	AM	**3**	66.6	28.3	27	163
	14:05-14:55	PM	**4**	59.2	12.4	40	107
	15:05-17:50	PM	**4**	60.1	14.7	31	108
11-Oct-12	9:05-9:55	AM	**2**	101.3	34.1	24	176
	10:05-12:50	AM	**2**	69.4	37.1	27	164
	14:05-14:55	PM	**1**	47.1	36.3	15	191
	15:05-17:50	PM	**1**	22.7	17.4	9	90
12-Oct-12	9:05-9:55	AM	**2**	172.4	27.9	101	235
	10:05-12:50	AM	**2**	92.6	29.2	46	176
	14:05-14:55	PM	**1**	42.7	9.0	29	65
	15:05-17:50	PM	**1**	29.2	9.1	11	64
13-Oct-12	9:05-9:55	AM	**4**	215.3	58.0	119	338
	10:05-12:50	AM	**4**	125.8	69.4	56	330
	14:05-14:55	PM	**3**	130.3	42.2	68	241
	15:05-17:50	PM	**3**	102.8	49.8	51	270
14-Oct-12	9:05-9:55	AM	**4**	153.4	69.2	69	298
	10:05-12:50	AM	**4**	40.2	16.0	18	86
	14:05-14:55	PM	**3**	32.7	7.9	20	55
	15:05-17:50	PM	**3**	23.6	8.6	10	53

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Table B4. Particle Number Concentration (#/L, >1.0 μm)

Date	Start - Stop	Session	Cond.	Average	Stdev	Min	Max
4-Oct-12	9:05-9:55	AM	**1**	227.3	108.0	102	476
	10:05-12:50	AM	**1**	145.8	58.2	63	311
	14:05-14:55	PM	**2**	264.0	38.9	203	401
	15:05-17:50	PM	**2**	214.8	50.5	155	579
5-Oct-12	9:05-9:55	AM	**1**	570.1	295.8	225	1297
	10:05-12:50	AM	**1**	107.7	54.6	28	270
	14:05-14:55	PM	**2**	151.2	11.8	129	188
	15:05-17:50	PM	**2**	113.8	30.0	68	244
6-Oct-12	9:05-9:55	AM	**3**	129.4	38.1	91	240
	10:05-12:50	AM	**3**	105.0	42.1	58	225
	14:05-14:55	PM	**4**	91.5	19.5	67	135
	15:05-17:50	PM	**4**	89.7	24.2	57	184
7-Oct-12	9:05-9:55	AM	**3**	172.5	67.6	97	358
	10:05-12:50	AM	**3**	109.0	44.0	46	239
	14:05-14:55	PM	**4**	105.4	18.5	80	184
	15:05-17:50	PM	**4**	105.2	23.6	58	176
11-Oct-12	9:05-9:55	AM	**2**	195.3	47.8	74	287
	10:05-12:50	AM	**2**	133.1	57.9	62	274
	14:05-14:55	PM	**1**	77.3	54.9	27	292
	15:05-17:50	PM	**1**	37.1	25.9	16	138
12-Oct-12	9:05-9:55	AM	**2**	329.1	41.8	211	420
	10:05-12:50	AM	**2**	169.7	48.7	90	296
	14:05-14:55	PM	**1**	66.6	12.1	49	97
	15:05-17:50	PM	**1**	47.5	14.3	22	98
13-Oct-12	9:05-9:55	AM	**4**	355.2	87.7	228	545
	10:05-12:50	AM	**4**	206.4	109.3	95	496
	14:05-14:55	PM	**3**	210.5	66.7	117	400
	15:05-17:50	PM	**3**	155.6	69.5	83	380
14-Oct-12	9:05-9:55	AM	**4**	269.0	111.8	125	499
	10:05-12:50	AM	**4**	76.4	28.1	40	146
	14:05-14:55	PM	**3**	56.5	13.8	34	102
	15:05-17:50	PM	**3**	39.6	13.4	17	83

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Table B1. Particle Number Concentration (#/L, >0.7 μm)

Date	Start - Stop	Session	Cond.	Average	Stdev	Min	Max
4-Oct-12	9:05-9:55	AM	**1**	331.3	144.1	166	657
	10:05-12:50	AM	**1**	194.0	77.8	85	383
	14:05-14:55	PM	**2**	381.8	36.0	320	518
	15:05-17:50	PM	**2**	327.9	60.0	249	715
5-Oct-12	9:05-9:55	AM	**1**	812.6	420.4	314	1807
	10:05-12:50	AM	**1**	141.3	69.5	41	328
	14:05-14:55	PM	**2**	208.0	15.0	178	246
	15:05-17:50	PM	**2**	161.7	40.0	107	330
6-Oct-12	9:05-9:55	AM	**3**	167.3	47.0	120	295
	10:05-12:50	AM	**3**	136.4	51.8	74	279
	14:05-14:55	PM	**4**	134.7	27.3	98	195
	15:05-17:50	PM	**4**	127.4	29.7	86	241
7-Oct-12	9:05-9:55	AM	**3**	223.7	84.4	129	451
	10:05-12:50	AM	**3**	145.8	57.7	62	365
	14:05-14:55	PM	**4**	149.4	23.1	120	245
	15:05-17:50	PM	**4**	148.7	30.1	92	245
11-Oct-12	9:05-9:55	AM	**2**	295.7	58.3	128	405
	10:05-12:50	AM	**2**	203.4	71.4	111	369
	14:05-14:55	PM	**1**	104.3	67.1	44	356
	15:05-17:50	PM	**1**	52.6	32.7	26	178
12-Oct-12	9:05-9:55	AM	**2**	461.4	52.5	301	578
	10:05-12:50	AM	**2**	240.0	65.9	128	402
	14:05-14:55	PM	**1**	87.8	14.5	64	119
	15:05-17:50	PM	**1**	63.3	18.1	33	125
13-Oct-12	9:05-9:55	AM	**4**	460.4	106.5	305	688
	10:05-12:50	AM	**4**	273.5	138.6	133	647
	14:05-14:55	PM	**3**	269.0	82.9	161	495
	15:05-17:50	PM	**3**	194.2	81.2	103	451
14-Oct-12	9:05-9:55	AM	**4**	360.7	138.1	181	642
	10:05-12:50	AM	**4**	112.3	38.5	63	205
	14:05-14:55	PM	**3**	77.8	19.2	49	137
	15:05-17:50	PM	**3**	54.2	17.2	28	108

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Table B2. Particle Number Concentration (#/L, >0.5 μm)

Date	Start - Stop	Session	Cond.	Average	Stdev	Min	Max
4-Oct-12	9:05-9:55	AM	**1**	548.6	210.5	305	1013
	10:05-12:50	AM	**1**	303.1	117.4	139	568
	14:05-14:55	PM	**2**	659.3	31.0	612	749
	15:05-17:50	PM	**2**	632.6	83.3	484	1013
5-Oct-12	9:05-9:55	AM	**1**	1387.3	712.6	556	2990
	10:05-12:50	AM	**1**	213.4	100.1	77	454
	14:05-14:55	PM	**2**	336.1	29.9	285	396
	15:05-17:50	PM	**2**	278.2	61.3	192	533
6-Oct-12	9:05-9:55	AM	**3**	248.4	67.7	182	433
	10:05-12:50	AM	**3**	201.3	68.2	118	389
	14:05-14:55	PM	**4**	230.6	43.1	168	322
	15:05-17:50	PM	**4**	209.7	39.4	164	358
7-Oct-12	9:05-9:55	AM	**3**	321.5	110.2	196	617
	10:05-12:50	AM	**3**	224.0	92.4	106	716
	14:05-14:55	PM	**4**	246.5	29.7	212	365
	15:05-17:50	PM	**4**	241.3	43.3	167	439
11-Oct-12	9:05-9:55	AM	**2**	633.5	83.2	349	742
	10:05-12:50	AM	**2**	464.5	99.2	308	683
	14:05-14:55	PM	**1**	192.2	94.5	100	539
	15:05-17:50	PM	**1**	102.4	48.1	55	279
12-Oct-12	9:05-9:55	AM	**2**	748.0	76.8	476	919
	10:05-12:50	AM	**2**	414.4	102.3	247	699
	14:05-14:55	PM	**1**	135.4	21.0	99	186
	15:05-17:50	PM	**1**	97.4	25.1	52	189
13-Oct-12	9:05-9:55	AM	**4**	638.5	134.7	434	906
	10:05-12:50	AM	**4**	405.8	186.0	215	912
	14:05-14:55	PM	**3**	388.2	113.7	243	689
	15:05-17:50	PM	**3**	271.0	96.5	160	562
14-Oct-12	9:05-9:55	AM	**4**	523.5	178.3	282	889
	10:05-12:50	AM	**4**	201.7	55.8	122	331
	14:05-14:55	PM	**3**	142.2	37.4	97	255
	15:05-17:50	PM	**3**	88.9	24.0	51	162

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Table B7. Particle Number Concentration (#/L, >0.3 μm)

Date	Start - Stop	Session	Cond.	Average	Stdev	Min	Max
4-Oct-12	9:05-9:55	AM	**1**	1804.8	554.2	1182	3070
	10:05-12:50	AM	**1**	1068.1	385.9	489	1902
	14:05-14:55	PM	**2**	2093.9	278.4	1635	2612
	15:05-17:50	PM	**2**	2281.2	263.9	1825	2842
5-Oct-12	9:05-9:55	AM	**1**	3215.9	1592.3	1364	6613
	10:05-12:50	AM	**1**	516.3	206.6	238	1050
	14:05-14:55	PM	**2**	909.6	145.0	665	1156
	15:05-17:50	PM	**2**	875.0	130.7	706	1239
6-Oct-12	9:05-9:55	AM	**3**	779.4	193.6	558	1262
	10:05-12:50	AM	**3**	594.5	129.9	431	902
	14:05-14:55	PM	**4**	746.5	133.2	571	1047
	15:05-17:50	PM	**4**	588.4	66.4	491	821
7-Oct-12	9:05-9:55	AM	**3**	1003.8	254.2	705	1637
	10:05-12:50	AM	**3**	906.8	246.2	646	2249
	14:05-14:55	PM	**4**	871.1	100.7	736	1161
	15:05-17:50	PM	**4**	755.8	111.7	610	1425
11-Oct-12	9:05-9:55	AM	**2**	7719.9	670.6	5532	8476
	10:05-12:50	AM	**2**	6024.7	725.7	5022	8137
	14:05-14:55	PM	**1**	2132.2	637.0	1336	3969
	15:05-17:50	PM	**1**	1144.2	349.4	714	2218
12-Oct-12	9:05-9:55	AM	**2**	3281.2	402.2	1897	3778
	10:05-12:50	AM	**2**	2541.4	346.3	2032	3651
	14:05-14:55	PM	**1**	606.9	112.2	468	836
	15:05-17:50	PM	**1**	391.1	89.2	243	639
13-Oct-12	9:05-9:55	AM	**4**	1606.9	322.6	1202	2655
	10:05-12:50	AM	**4**	1188.4	257.1	885	1881
	14:05-14:55	PM	**3**	2098.9	711.3	1171	3592
	15:05-17:50	PM	**3**	1039.8	159.2	781	1641
14-Oct-12	9:05-9:55	AM	**4**	1191.1	304.4	793	1814
	10:05-12:50	AM	**4**	814.4	151.0	615	1206
	14:05-14:55	PM	**3**	978.4	338.3	599	1727
	15:05-17:50	PM	**3**	420.1	88.8	251	649

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Appendix C. Summary figures of response for each PAQ/SBS variable

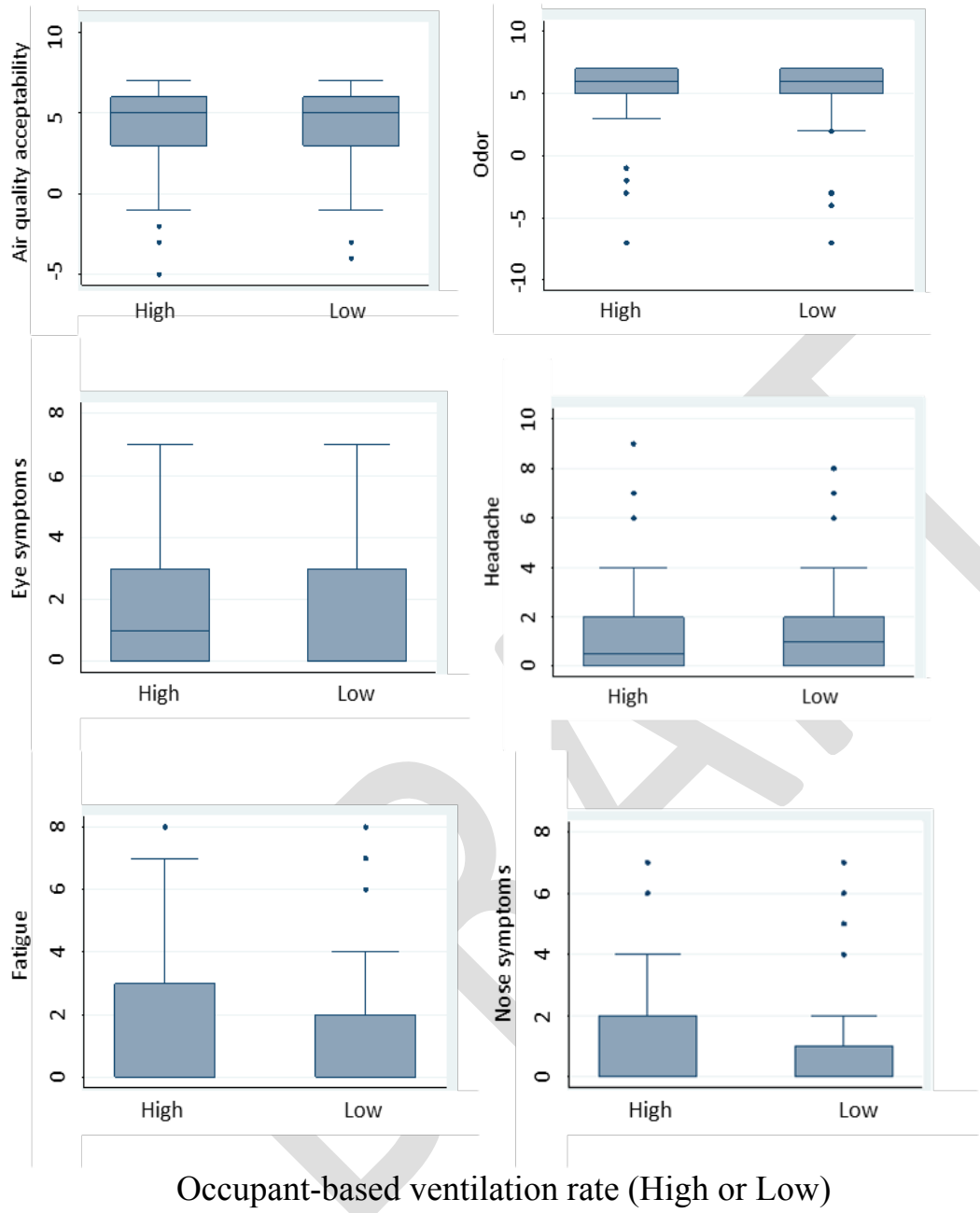

Figure C1. Distributions of continuous outcomes for the occupant-based ventilation scenarios for six PAQ/SBS variables. The actual ventilation rates associated with the "high" and "low" characterization are provided in Table 5. For "air quality acceptability and odor, the y-axis shows acceptability on a 7-point scale ranging from "just barely acceptable" to "completely acceptable", or from "just barely unacceptable" to "complete unacceptable". For remaining variables, the y-axis shows current severity of health symptoms on a 10-point scale.

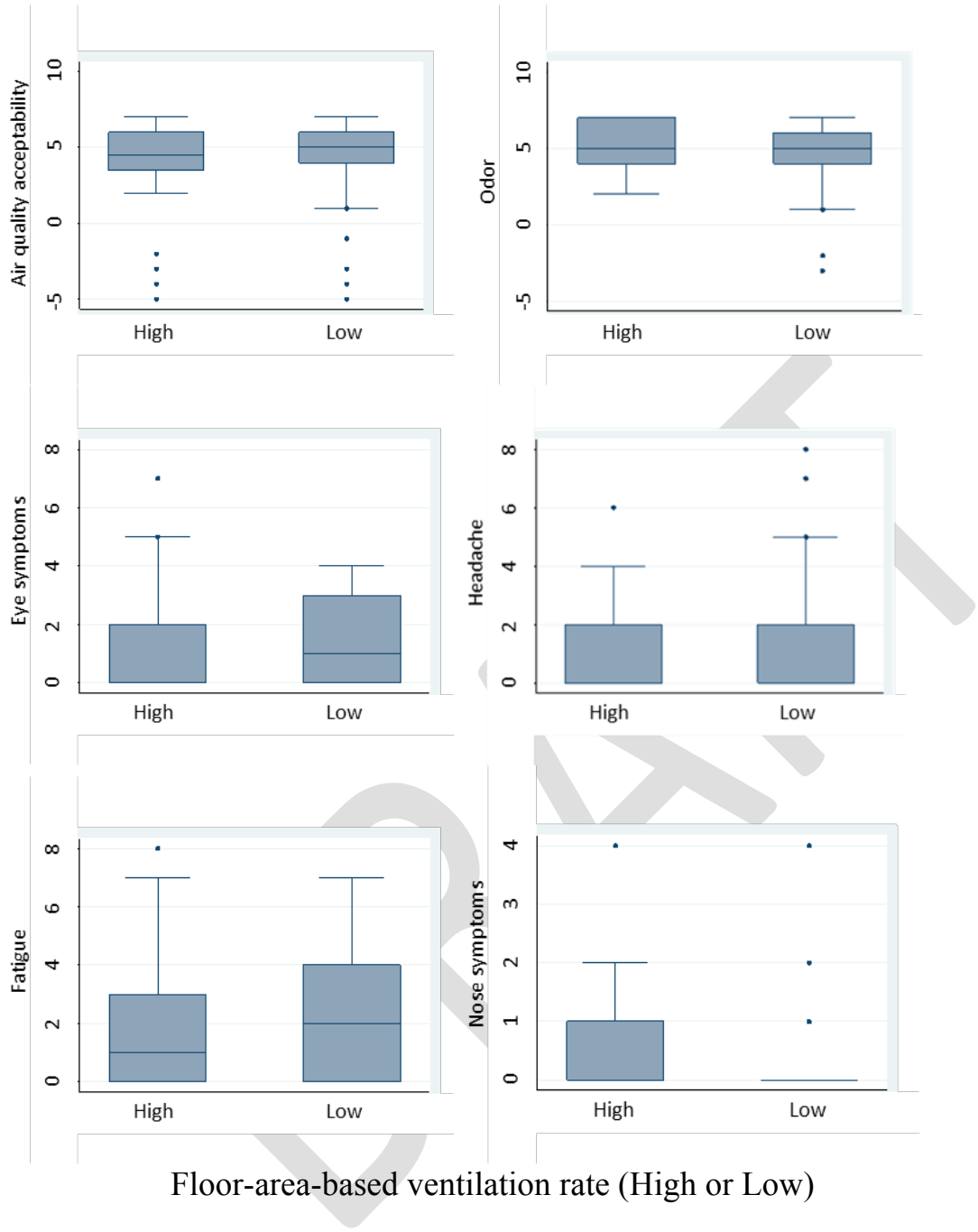

Figure C1. Distributions of continuous outcomes for the floor-area-based ventilation scenarios for six PAQ/SBS variables. The actual ventilation rates associated with the "high" and "low" characterization are provided in Table 5. For "air quality acceptability and odor, the y-axis shows acceptability on a 7-point scale ranging from "just barely acceptable" to "completely acceptable", or from "just barely unacceptable" to "complete unacceptable". For remaining variables, the y-axis shows current severity of health symptoms on a 10-point scale.