Green Buildings and Health

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GREEN BUILDINGS AND HEALTH

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GREEN BUILDINGS AND HEALTH

ABSTRACT

40 years of public health research on buildings has identified the indoor environmental drivers of health and productivity. Concurrently, increased environmental awareness spurred the green building movement with the goal of encouraging more sustainable buildings. The question remains as to whether green buildings are also healthy buildings.

The objective of this dissertation is to investigate the impact of green buildings on health and cognitive function in both laboratory and real-world settings, and furthermore quantify these impacts in comparison to the potential environmental and economic costs. First, 24 participants spent 6 work days in a controlled office environment. On different days, they were exposed to conditions representative of Conventional (high volatile organic compound (VOC) concentration), Green (low VOC concentration), and Green+ (low VOC concentration and increased ventilation) office buildings. Additional conditions tested artificially elevated carbon dioxide (CO_2) levels. On average, cognitive scores were 61% higher on the Green building day and 101% higher on the Green+ building days than on the Conventional building day ($p<0.0001$). VOCs and CO_2 were independently associated with cognitive scores.

Second, based on the finding of improved cognitive scores in buildings with enhanced ventilation, the productivity benefits were compared to the environmental and economic costs of doubling ventilation rates. The costs were less than $40 per person per year in all climate zones investigated, while the benefits in terms of productivity exceeded $6,500 per person per year.

The environmental impacts could be mitigated through the implementation of energy recovery ventilators (ERVs).

Lastly, we conducted building assessments of 10 high-performing buildings (i.e. buildings surpassing the ASHRAE 62.1-2010 ventilation requirement and with low VOC concentrations) in 5 cities around the U.S. while tracking the health and productivity of office workers in those buildings. Even among high-performing buildings, workers in green certified buildings scored 26.4% higher on cognitive function tests than those in non-certified buildings. Sleep Quality scores were 6.4% higher in green certified buildings, suggesting an impact of the building on sleep quality.

We show significant benefits to cognitive function and health in green buildings through multiple experimental approaches, driven by factors consistent with the public health literature.

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THESIS OVERVIEW

The environments in which we spend time play a significant role in our overall well-being. Given that we spend 90% of our time indoors, buildings have an outsized, and often underappreciated, impact on our health. Over the past century, building practices have changed contrary to the research on health in buildings and each time led to serious health consequences. Rapidly constructed homes following World War II used new building materials that had not properly offgassed (Gerber, 2000). The high levels of VOCs such as formaldehyde caused a pattern of illness in occupants of these homes, even though some of the health risks of formaldehyde had been established previously (Industrial Hygiene Research, 1945). Again in the 1970s, air exchange rates were lowered in response to higher energy prices despite 60 years of ventilation standards that cautioned against inadequate ventilation (Persily, 2015). The resulting health impacts, termed Sick Building Syndrome (SBS), have been rigorously documented in the subsequent years (Redlich et al., 1997; Riesenberg et al., 1986).

More recently, another change in buildings practices arose with the inception of the green building movement. In contrast to the examples above, it sought to improve the energy performance of a building while simultaneously ensuring an adequate indoor environment for the occupants. However, the fulfillment of this goal in practice has been brought into question as these buildings became more prevalent. The public health literature generally supports that green buildings have improved indoor environmental quality (IEQ), improved occupant perceptions, and fewer SBS symptoms, but the studies to date mostly lack objective measurements of health, which may cause considerable bias as participants are not blinded to their building classification (Allen et al., 2015). These studies are also limited in their assessments of health, focusing on acute symptomatic outcomes and ignoring chronic or worker performance outcomes.

This thesis is intended to address these limitations in the literature. Through two experimental approaches, one in which participants were blinded to their building classification and one in which participants were tested in their current building, we tested the impact of building classification on an objective measure of worker performance – cognitive function. The appended publications describe the methods and results of these efforts, which have the following aims:

Paper 1	*Associations of Cognitive Function Scores with Carbon Dioxide, Ventilation, and Volatile Organic Compound Exposures in Office Workers: A Controlled Exposure Study of Green and Conventional Office Environments*
Aim 1	To **simulate** IEQ conditions found in Green and Conventional buildings and evaluate the impacts on objective and subjective measures of human health and cognitive function.
Paper 2	Economic, Environmental and Health Implications of Enhanced Ventilation in Office Buildings
Aim 2	To **quantify** the benefits of improved cognitive function in green buildings and compare to environmental and economic costs
Paper 3	*The Impact of Working in a Green Certified Building on Cognitive Function and Health*
Aim 3	To **observe** IEQ conditions found in high-performing, green certified and high-performing, non-certified buildings and evaluate the impacts on objective and subjective measures of human health and cognitive function.

CHAPTER 1 - Associations of Cognitive Function Scores with Carbon Dioxide, Ventilation, and Volatile Organic Compound Exposures in Office Workers: A Controlled Exposure Study of Green and Conventional Office Environments

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Abstract

Background: The indoor built environment plays a critical role in our overall wellbeing, both due to the amount of time we spend indoors (~90%) and the ability of buildings to positively or negatively influence our health. The advent of sustainable design or green building strategies reinvigorated questions regarding the specific factors in buildings that lead to optimized conditions for health and productivity.

Objective: To simulate indoor environmental quality (IEQ) conditions in "Green" and "Conventional" buildings and evaluate the impacts on an objective measure of human performance – higher order cognitive function.

Methods: Twenty-four (24) participants spent 6 full work days (9 a.m. – 5 p.m.) in an environmentally controlled office space, blinded to test conditions. On different days, they were exposed to IEQ conditions representative of Conventional (high volatile organic compound (VOC) concentration) and Green (low VOC concentration) office buildings in the U.S. Additional conditions simulated a Green building with a high outdoor air ventilation rate (labeled Green+) and artificially elevated carbon dioxide (CO_2) levels independent of ventilation.

Results: On average, cognitive scores were 61% higher on the Green building day and 101% higher on the two Green+ building days than on the Conventional building day ($p<0.0001$). VOCs and CO_2 were independently associated with cognitive scores.

Conclusions: Cognitive function scores were significantly better in Green+ building conditions compared to the Conventional building conditions for all nine functional domains. These findings have wide ranging implications because this study was designed to reflect conditions that are commonly encountered every day in many indoor environments.

1.1 Introduction

The increasing cost of energy in the 1970s led to a change in building practices throughout the United States, as buildings were increasingly constructed to be airtight and energy efficient. This is reflected in decreasing air exchange rates in homes and buildings. For homes, beginning around this time period, typical air exchange rates began decreasing from approximately 1 air change per hour (ACH) to approximately 0.5 ACH (Chan et al. 2003; Hodgson et al. 2000; ASHRAE 2013). Homes built in the past decade are designed to be even more energy-efficient and therefore can be even tighter (0.1 - 0.2 ACH; Allen et al. 2012; ASHRAE 2013). The 100+ year story of ventilation in buildings is more complicated, and neatly summarized recently by Persily (2015). Persily describes the original ASHRAE 62 standard, issued in 1973, and the many subsequent iterations (e.g. ASHRAE 62.1 applies to commercial buildings), demonstrating the evolving nature of our understanding regarding the relationship between ventilation rate and acceptable indoor air quality. Similar to the story with homes, commercial ventilation requirements were lowered in the early 1980's, largely as an energy-conservation measure (Persily 2015).

With these design changes comes the potential for negative consequences to indoor environmental quality (IEQ), as decreased ventilation can lead to increased concentration of indoor pollutants. Building-related illnesses and sick building syndrome (SBS) were first reported in the 1980s as ventilation rates decreased (Riesenberg and Arehart-Treichel 1986), with significant annual costs and productivity losses due to health symptoms attributable to the indoor environment (Fisk et al. 1997). A few factors of the indoor and work environment have been found to be associated with occupant health. These include environmental measures, such as humidity; building factors, such as ventilation rate; workspace factors, such as the presence of chemical-emitting materials; and personal factors, such as job stress, allergies, and gender (Mendell 1993; Wargocki et al. 2000; Bornehag et al. 2005; Hedge 2009; Hedge and Gaygen 2010; Nishihara 2014).

The IEQ problems that arose from conventional buildings with a tight envelope contributed to the advent of sustainable design or "green" building rating systems (e.g. U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED®)). These rating systems aim to reduce the environmental footprint of buildings and improve occupant health by providing design credits to new and existing buildings for adopting green design, operation, and maintenance. Different levels of ratings for the building are then awarded based on the number of acquired credits (e.g., silver, gold, platinum) (USGBC 2014). Many design credits are aimed at energy efficiency and environmental performance, but also include guidelines for improving ventilation and filtration, using low-emitting materials, controlling indoor chemical and pollutant sources, improving thermal and lighting conditions, and offering daylight views to building occupants (USGBC 2014). Compared to conventional buildings, environmental measurements in green buildings show lower concentrations of several key pollutants including particles, nitrogen dioxide, VOCs, and allergens (Colton et al. 2014; Jacobs et al. 2014; Noris et al. 2013). However, these reductions generally did not extend to CO_2 or air exchange rate, demonstrating the influence of energy efficiency on green building operation and design. Green buildings were associated with improved IEQ, and have been associated with reductions in self-reported symptoms in people inhabiting the buildings, and with improved productivity in home, school, and office settings (Colton et al. 2014; NRC 2007; Singh et al. 2010). However, an important limitation of these studies is the reliance on subjective outcome measures, such as surveys, that have the potential for bias because participants are aware of their status (i.e. green or control). To our knowledge, no studies have been conducted in green buildings to date where participants are blinded to their building condition (Allen et al. 2015).

We designed this study to objectively quantify the impact of indoor environmental on higher order cognitive function, a driver of real-world productivity in office workers. We simulated low VOC ("Green") and high VOC ("Conventional") building conditions, both at the ASHRAE standard ventilation rate. Recognizing that technological advances in mechanical systems opens the possibility of increasing ventilation rates without sacrificing energy efficiency, we also tested another building condition that introduced higher rates of ventilation to the Green building condition. This condition is labeled Green+. Last, we were motivated by the recent findings by Satish et al. that CO_2 may be a direct pollutant, and not just an indicator of ventilation (2012), and therefore estimated associations of full workday exposure to CO_2 on cognitive function holding all other variables constant.

1.2 Methods

1.2.1 Study Design

This is a study undertaken in a controlled office environment to estimate the effect of several indoor environmental quality parameters on an objective measure of cognitive function. We utilized a double-blinded study design that includes repeated measures of cognitive function on the same individual, characterization of potential confounding IEQ variables, and mid-week testing to avoid Monday/Friday effects. All participants received the same exposures on each day, with exposures varying each day.

1.2.2 Study Population

24 professional-grade employees (architects, designers, programmers, engineers, creative marketing professionals, managers) in the Syracuse area participated in a six day longitudinal study of cognitive performance and building conditions (Table 1.1). Six additional people were originally recruited as backups but were not enrolled in the study. Participants were recruited through emails to local businesses. The study population was restricted to non-sensitive persons by excluding current smokers and people with asthma (due to testing indoor air quality), claustrophobia or schizophrenia (due to this being a laboratory experiment where participants are required to remain in the TIEQ). The participants were relocated to the Willis H. Carrier Total Indoor Environmental Quality (TIEQ) Laboratory at the Syracuse Center of Excellence (CoE) for six days over the course of two weeks in November of 2014. The study protocol was reviewed and approved by the Harvard T.H. Chan School of Public Health Institutional Review Board. SUNY Upstate Medical and Syracuse University ceded their review to Harvard's IRB. All participants signed informed consent documents and were compensated $800.

Table 2.1 Participant demographics.

	n	%
Gender		
Male	10	42
Female	14	58
Age		
20-30	8	33
31-40	3	12
41-50	6	25
51-60	4	17
61-70	3	12
Ethnicity		
White/Caucasian	22	92
Black or African American	1	4
Latino	1	4
Highest level of Schooling		
High School Graduate	1	4
Some College	2	8
College Degree	13	54
Graduate Degree	8	33
Job Category		
Managerial	5	21
Professional	15	63
Technical	1	4
Secretarial or Clerical	1	4
Other	2	8

Participants reported to the CoE on Tuesday, Wednesday and Thursday, at 9 a.m., for two consecutive weeks. The CoE has two nearly identical office environments located adjacent to one another as part of the TIEQ Lab, each with 12 cubicles. The rooms are similarly constructed and have identical building materials (e.g., carpeting, cubicles, painting, computers). Environmental conditions, described in the following sections, were designed to be consistent in the two rooms. On the first day participants were randomly assigned to a cubicle in the TIEQ Lab for the duration of the study. Participants were requested to spend the entire work day in the simulated office environments performing their normal work activities. They were provided with computers, internet access, and an area for private telephone calls and printing. A 45-minute lunch break was given between 12:00-12:45 (Room 1) or 12:15-1:00pm (Room 2). A limited selection of food was provided, served and eaten in a room adjacent to the two simulated office environment rooms. Participants then returned to the simulated office environment to continue their work. Cognitive testing was initiated at 3:00 p.m. each day, after which the participants completed the daily surveys and left the TIEQ Lab. Participants were blinded to test conditions, as were the analysts performing the cognitive function assessment. Participants were not given any instructions on how to spend their time in the evenings or on the Mondays before starting the test period.

1.2.3 Indoor Environment Simulation

The different environmental simulations in the TIEQ Lab on each day were designed to evaluate commonly encountered conditions and guidance values (Table 1.2). The three test parameters that were experimentally controlled were ventilation with outdoor air, CO_2, and VOCs. We selected two outdoor air ventilation rates for this study: 20 cfm/person and 40 cfm/person. LEED® specifies that mechanically ventilated spaces must meet ventilation rates under ASHRAE 62.1, or local equivalent, whichever is more stringent (USGBC 2014; ASHRAE 2013). Many local building codes use the previous ASHRAE standard of 20 cfm/person, which corresponds to an indoor CO_2 concentration of 945 ppm. Therefore, 20 cfm/person was the ventilation rate we used for the Green and Conventional simulation days because it reflects the minimum required ventilation rate for both green buildings (through LEED®) and conventional buildings (through ASHRAE). We also sought to evaluate the impact of a doubling of that minimum rate to 40 cfm/person (labeled Green+ days), which corresponds to an approximate steady-state CO_2 concentration of 550 ppm. To ensure blinding, air movement was maintained at 40 cfm per person on all study days, with 100% outdoor air ventilation used on Green+ days and moderate and high CO_2 days, and a mix of 50% outdoor air and 50% recirculated air used on the Green and Conventional days to achieve 20 cfm outdoor air ventilation per person.

Table 1.2 Average indoor environmental conditions simulated in each room of the TIEQ lab.

Variable	Day 1 Green+		Day 2 Moderate CO_2		Day 3 High CO_2		Day 4 Green		Day 5 Conventional		Day 6 Green+	
Date	11/4		11/5		11/6		11/11		11/12		11/13	
Day of the Week	Tue		Wed		Thu		Tue		Wed		Thu	
Room	502	503	502	503	502	503	502	503	502	503	502	503
Experimental Parameters												
CO_2 (ppm)	563	609	906	962	1400	1420	761[b]	726[b]	969	921	486	488
Outdoor Air Ventilation (cfm/person)[a]	40	40	40	40	40	40	20	20	20	20	40	40
TVOCs ($\mu g/m^3$)	43.4	38.5	38.2	28.6	32.2	29.8	48.5	43.5	506	666	55.8	14.9
Other Environmental Parameters												
Temp (°C)	23.9	24.5	22.4	23.9	21.3	22.0	22.9	23.7	21.8	22.5	20.7	21.3
RH (%)	31.0	30.4	34.2	31.6	38.7	38.3	34.3	33.3	39.6	38.3	27.8	26.8
NO_2 ($\mu g/m^3$)	57.9	58.9	53.2	54.1	60.8	58.4	51.3	45.6	54.6	50.8	56.5	55.5
O_3 ($\mu g/m^3$)	3.42	21.2	14.4	13.0	1.37	0.00	6.85	238	1.71	1.37	4.11	6.85
$PM_{2.5}$ ($\mu g/m^3$)	2.38	3.49	3.35	2.58	2.97	2.42	1.26	1.83	1.68	1.34	1.26	1.38
Noise (dB)	51.3	49.9	49.7	48.8	52.5	48.8	49.6	48.7	51.1	48.8	50.5	49.2
Illuminance (mV)	2.95	2.70	2.89	2.83	2.31	2.04	3.11	2.93	2.74	2.51	2.39	2.28
Irradiance (mV)	9.07	8.76	9.45	9.37	6.00	6.05	9.90	9.60	8.30	8.14	6.70	6.82

[a] A constant air flow rate of 40 cfm/person was maintained on all study days, with 100% outdoor air used on days 1, 2, 3, and 6, and 50% outdoor air and 50% recirculated air used to achieve an outdoor air ventilation rate of 20 cfm/person on days 4 and 5.

[b] Average concentration from 2-5 p.m. was 926 ppm, but lower CO_2 concentrations in the morning hours during the approach to steady-state led to a lower average CO_2 concentration.

For the assessment of the independent association of CO_2 on cognitive function, outdoor air ventilation rate held constant at 40 cfm/person while CO_2 was added to the chambers to reach three steady-state CO_2 concentrations. The first target was 550 ppm (Green+, Days 1 and 6). The second target, 945 ppm, was selected to reflect a level that would be expected at the previously described ASHRAE minimum recommended ventilation rate of 20 cfm outdoor air/person. The third target, 1400 ppm, was selected to represent a higher, but not uncommon, concentration of CO_2 found in indoor environments (1400 ppm is the maximum observed 8-hour time-weighted-average CO_2 concentration in the USEPA BASE dataset (USEPA 1998)). On Days 2 and 3, where the independent effects of CO_2 were tested, CO_2 was added from a cylinder of ultra-pure CO2 (at least 99.9999% pure) to the TIEQ Lab supply air at the rate needed to maintain steady-state CO_2 concentrations of 945 ppm and 1,400 ppm. Since CO_2 concentrations are impacted by occupancy and mixing impact concentrations, a technician monitored CO_2 in real-time and adjusted the emission rate accordingly to keep CO_2 concentrations constant. During Days 4 and 5 (Green and Conventional), injection of pure CO_2 was not needed to reach the target CO_2 concentrations because of the reduced outdoor ventilation rate. A protocol was established to ensure participant safety in the event that there were unexpected deviations. CO_2 was monitored in real-time at a high-spatial resolution in the test rooms, using three different and independently calibrated monitors. A technician seated next to the CO_2 shut-off valves monitored the CO_2 concentrations during the entire test period. The protocol called for immediately canceling of the testing if CO_2 concentrations exceeded preset thresholds that were set well-below occupational health limits (2,500 ppm; one-half of the Threshold Limit Value set by the American Conference of Governmental Industrial Hygienists (ACGIH 2015)). No deviations from protocol occurred during the study.

The TIEQ Lab was constructed with low-VOC materials, and low levels of VOCs were confirmed by pre-testing (Table 1.3). To simulate a Conventional office space with higher VOCs, we placed VOC sources in the diffuser that supplied air to each cubicle area before the participants arrived on Day 5. We selected a target total VOC (TVOC) level of 500 $\mu g/m^3$ based on the LEED® Indoor Air Quality Assessment credit limit, as measured using EPA method TO-15 (USGBC 2014). The diffusers are built into the floor of the TIEQ Lab and there were no visible indicators of these sources for the participants to observe. We selected a mix of non-odor sources to simulate VOC-emitting materials that are commonly found in office building and which cover four indoor VOC source categories including building materials (56 in^2 exposed edge melamine, 56 in^2 exposed edge particle board, 64 in^2 vinyl mat), adhesives [80 in^2 duct tape, 80 in^2 packing tape (exposed)], cleaning products (1 oz. multi-surface cleaner, 4 multi-surface wipes, 144 in^2 recently dry-cleaned cloth), and office supplies (4 dry erase markers, 1 open bottle of whiteout).

Table 1.3 Speciated VOC concentrations (μg/m^3) on each study day, averaged across rooms.

Analyte	Condition						
	Background	Green+	Med. CO_2	High CO_2	Green	Conventional	Green+
VOCs							
1,2,4-Trimethylbenzene	0.3	0.2	ND[a]	0.1	ND	0.5	0.1
2-Butanone	2.5	0.7	0.7	0.8	1.1	1.1	0.6
2-Propanol	1.0	1.2	1.1	3.1	1.2	312.5	8.2
Acetone	12.0	14.7	9.6	8.7	20.0	20.0	8.6
Benzene	0.5	0.8	0.5	0.9	0.7	0.5	0.5
Carbon disulfide	0.6	0.2	ND	ND	ND	ND	0.1
Carbon tetrachloride	ND	0.2	0.4	ND	0.2	ND	ND
Chloroform	ND	0.1	ND	ND	ND	0.1	ND
Chloromethane	1.3	1.7	1.5	1.4	1.9	1.5	1.4
Cyclohexane	0.2	0.3	0.4	0.5	0.1	0.4	0.3
Dichlorodifluoromethane	2.5	2.6	2.9	2.7	2.9	2.4	2.5
Ethyl acetate	ND	ND	ND	ND	1.0	2.0	ND
Ethylbenzene	0.3	0.4	ND	0.3	0.2	0.1	0.1
Freon 113	0.3	0.7	0.8	0.8	0.8	0.2	0.4
Heptane	ND	0.3	ND	0.3	ND	257.5	6.9
Hexane	0.4	0.7	0.5	0.7	0.4	0.8	1.3
m,p-Xylene	0.8	1.5	0.4	1.0	1.0	0.7	0.7
Methylene chloride	0.5	0.3	0.6	0.5	0.3	0.4	0.4
o-Xylene	0.3	0.4	ND	0.4	0.1	0.3	0.1
Styrene	0.1	ND	ND	ND	ND	ND	0.1
Tetrachloroethene	3.7	0.9	ND	ND	0.9	0.6	0.2
Tetrahydrofuran	ND	ND	ND	ND	0.2	0.1	0.2
Toluene	2.4	2.1	1.4	1.9	2.2	1.9	2.9
trans-1,2-Dichloroethene	19.0	8.8	12.6	6.2	10.3	21.8	8.7
Trichloroethene	ND	ND	ND	ND	ND	ND	0.2
Trichlorofluoromethane	1.3	1.2	1.6	1.4	1.5	1.1	1.2
Grand Total	50.0	40.1	35.0	31.4	46.9	626.4	45.6
Aldehydes							
2,5-Dimethylbenzaldehyde	ND	ND	ND	ND	ND	ND	ND
Acetaldehyde	1.0	3.7	3.2	3.1	5.4	7.3	2.1
Benzaldehyde	ND	ND	ND	ND	ND	1.5	ND
Crotonaldehyde	ND	ND	ND	ND	ND	ND	ND
Formaldehyde	2.4	5.9	5.5	5.4	8.9	11.7	4.4
Hexanaldehyde	ND	0.8	0.8	ND	1.9	2.4	ND
Isovaleraldehyde	ND	ND	ND	ND	ND	ND	ND
m,p-Tolualdehyde	ND	ND	ND	ND	ND	ND	ND
n-Butyraldehyde	1.1	2.7	1.4	2.3	2.8	2.4	2.0
o-Tolualdehyde	ND	ND	ND	ND	ND	ND	ND
Propionaldehyde	ND	0.7	1.2	ND	1.4	1.6	0.6
Valeraldehyde	ND	ND	ND	ND	ND	ND	ND
Glutaraldehyde	ND	0.5	ND	ND	0.4	ND	ND
o-Pthalaldehyde	ND	65.1	57.7	70.0	41.6	38.4	76.8
Grand Total	4.6	79.4	69.8	80.9	62.4	65.3	85.8

[a] Non-detect

1.2.4 Environmental Monitoring

The study team characterized the TIEQ Lab on each test day for a wide range of IEQ indicators: CO_2, temperature, relative humidity, barometric pressure, sound levels, VOCs, aldehydes, NO_2, O_3, $PM_{2.5}$, and light. Netatmo Weather Stations were installed in each cubicle to measure temperature, humidity, carbon dioxide concentrations in parts per million (ppm), and sound levels (in decibels) every 5 minutes for each participant. They were calibrated to 0 and 3000 ppm of CO_2 using calibration gases and validated using a calibrated TSI Q-Trak (model 7575). In addition, the Netatmos were tested with 400 and 1000 ppm calibration gas at the end of the study to determine if the sensors drifted during the two week period. Duplicate measures of CO_2 were collected in each room using a TSI Q-Trak model 7575 and two K-33 data loggers. Summa canisters were used to detect overall levels of 62 common VOCs in a randomly selected workstation in each room for each of the study days (Table 1.3). An additional sample was collected in a third randomly selected cubicle each day. Samples were analyzed by ALS Laboratories according to EPA method TO-15. 36 VOCs were not detected in any of the samples.

In each room a monitoring station was placed at the far end of the room from the entrance to monitor additional IEQ parameters. The station included a) a TSI SidePak AM510 personal aerosol monitor to measure particulate matter 2.5 microns in diameter or smaller ($PM_{2.5}$) , b) an integrated filter sample for gravimetric analysis of $PM_{2.5}$ and elemental composition, c) an 8-hour integrated active air sample (0.4 L/min flow rate) analyzed for 14 aldehydes by ALS Analytical Laboratories using EPA method TO-11, d) a passive NO_2 badge (8-hour time-weighted average; model X-595, Assay Technology; OSHA method 182), e) a passive sampling badge for ozone O_3 (8-hour time-weighted average; model X-586, Assay Technology; OSHA Method 214), and e) illuminance and irradiance measures using an IL1400 radiometer/powermeter with SEL-033/Y/W and SEL-033/F/W detectors. VOC, aldehyde, NO_2, O_3, and integrated $PM_{2.5}$ samples had at least one blank and one duplicate for every 10 samples. Samples were blank corrected for analyses. All duplicate measures were within 15% of each other, and an average of the two was used for subsequent analyses.

An ambient air monitoring system was installed on the roof of the CoE to measure $PM_{2.5}$, O_3, and NO_2 using the same procedures and equipment as the indoor stations to establish the potential influence of outdoor contaminants on the indoor environment. Outdoor temperature, humidity, solar radiation, and wind speed/direction data was obtained from the CoE weather station located on the roof of the building. Baseline (i.e. prior to occupancy) measurements of all IEQ parameters were collected in the TIEQ Lab one month before the actual study.

1.2.5 Cognitive Function Assessment

The cognitive assessment was performed daily using the Strategic Management Simulation (SMS) software tool, which is a validated, computer-based test, designed to test the effectiveness of management-level employees through assessments of higher-order decision making (Streufert et al. 1988; Breuer et al. 2003; Satish et al. 2004). At the start of the 1.5 hour test, participants were given a brief, 1-page description of the scenario that they were about to participate in during the test. They were then logged onto a standardized desktop computer station at the TIEQ Lab using a unique identifier. Participants were not allowed to use their own computers and were instructed to turn off all other devices prior to the assessment. The simulation was then initiated. Participants were exposed to diverse situations based on real-world equivalent challenges (e.g. handling a township in the role of a mayor or emergency coordinator). These scenarios are designed to capture participants' standard response pattern. The software allows flexibility in approach; participants can choose to make a decision or form a plan at any time in response to any stimulus from the program. The absence of requirements or stated demands allows the participant the freedom to strategize and take initiative in his or her typical cognitive style. Based on the participant's actions, plans, responses to incoming information, and use of prior actions and outcomes, the SMS software computes scores for nine cognitive factors (Table 1.4).

Table 1.4 Description of the cognitive domains tested.

Cognitive Function Domain[a]	Description
Basic Activity Level	Overall ability to make decisions at all times
Applied Activity Level	Capacity to make decisions that are geared toward overall goals
Focused Activity Level	Capacity to pay attention to situations at hand
Task Orientation	Capacity to make specific decisions that are geared toward completion of tasks at hand
Crisis Response	Ability to plan, stay prepared and strategize under emergency conditions
Information Seeking	Capacity to gather information as required from different available sources
Information Usage	Capacity to use both provided information and information that has been gathered toward attaining overall goals
Breadth of Approach	Capacity to make decisions along multiple dimensions and use a variety of options and opportunities to attain goals
Strategy	Complex thinking parameter which reflects the ability to use well integrated solutions with the help of optimal use of information and planning

[a] See Streufert et al. 1986 for detailed descriptions

A technician trained in administering this test was present to provide standardized instructions and periodically answer any questions from participants. Parallel scenarios (i.e., equivalent scenarios) were used from one day to the next, which allow retesting individuals without potential bias due to experience and learning effects (Swezey et al. 1998). Parallel scenarios have correlation coefficients between 0.68 and 0.94 for the scores on these cognitive function domains (Streufert et al. 1988).

1.2.6 Statistical Analyses

Generalized additive mixed effect models were used to test associations between environmental exposures and cognitive function while controlling for the correlated-nature of the repeat measures. In the model, the most specific exposure was assigned to each participant, whether it be cubicle-level (CO_2), room-level (VOCs), or lab-level (ventilation). Participant ID was treated as a random intercept to control for confounding by individual characteristics. The residuals were normally distributed and homoscedastic for all models (data not shown). We used penalized splines to graphically assess linearity in the associations between environmental exposures and cognitive scores. SMS scores are often compared to normative data from other uses of the SMS software (e.g. Satish et al. 2012). Since we did not have access to normative data, we instead used our study population as the reference group. Based on the analysis, cognitive scores were normalized by Conventional (Table 1.5), Green (Figure 1.1) or Green+ (Figure 1.2) scores to allow for comparisons across cognitive function domains, each of which has a unique scale in their raw form. The scores were normalized for each cognitive domain by dividing all scores by the average score during the normalizing condition. The statistical significance of our results is not affected by normalization. Given the multiple comparisons tested in this analysis, p-values below 0.001 were considered statistically significant according to a Bonferroni correction. Analyses were performed using the open-source statistical package R version 3.0.0 (R Project for Statistical Computing, Vienna, Austria).

1.3 Results

1.3.1 Green Building and Cognitive Function

The TVOC levels were constant at <50 µg/m^3 on all study days except the Conventional building day when levels increased to 506–666 µg/m^3 depending on the room. The compounds that increased in concentration include but are not limited to formaldehyde, benzaldehyde, acetaldehyde, heptane, and 2-propanol. Heptane and 2-propanol had the largest increases of the compounds sampled (Table 1.3). Total aldehyde concentrations were primarily driven by o-Pthalaldehyde and remained relatively constant on all study days.

Cognitive function scores were higher in Green building conditions compared to the Conventional building condition for all nine functional domains (Figure 1.1). On average, cognitive scores were 61% higher on the Green building day and 101% higher on the two Green+ building days than on the Conventional building day. The largest effects were seen for Crisis Response, Information Usage, and Strategy, all of which are indicators of higher level cognitive function and decision-making (Streufert 1986). For Crisis Response, scores were 97% higher for the Green condition compared to Conventional, and 131% higher comparing Green+ and Conventional. For Information Usage, scores in the Green and Green+ conditions were 172% and 299% higher than Conventional, respectively. And for Strategy, which tests the participants' ability to plan, prioritize and sequence actions, the Green and Green+ day scores were 183% and 288% higher than on the Conventional day (Table 1.5).

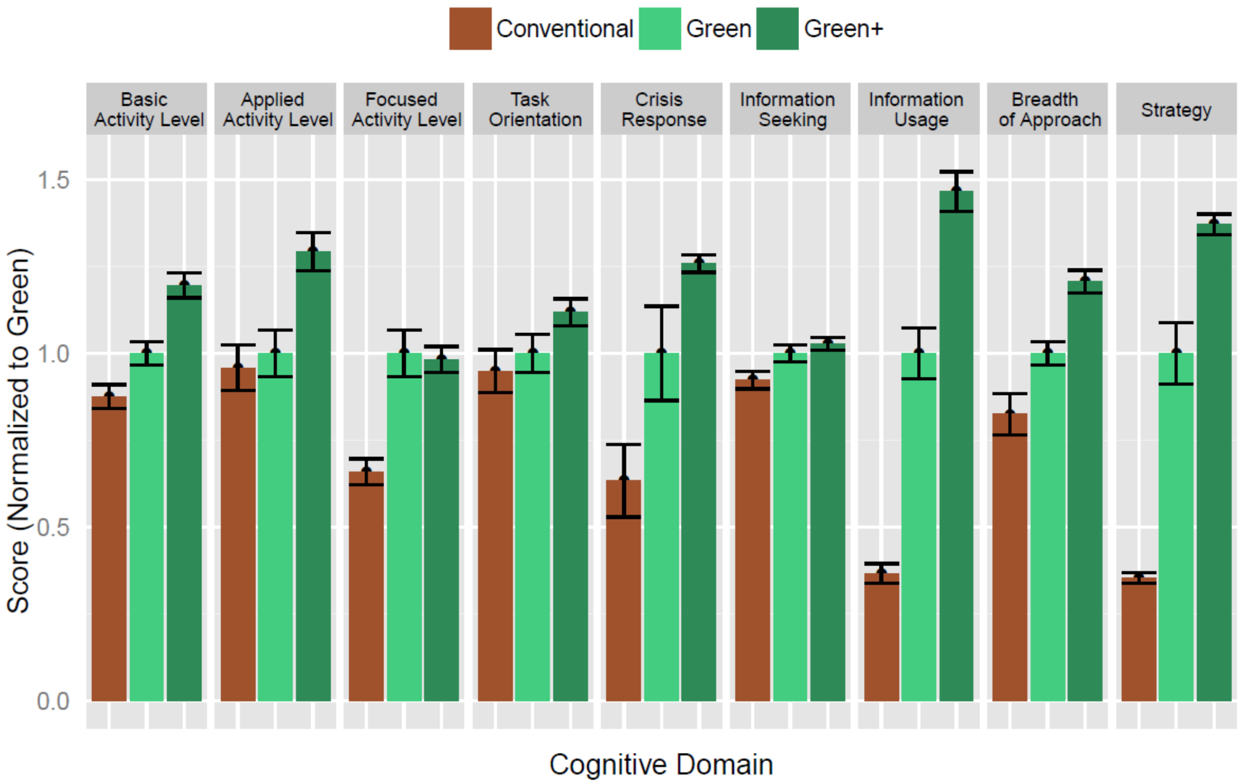

Figure 1.1 Average cognitive function scores and standard error bars by domain for the Conventional, Green and two Green+ conditions, normalized to the Green condition by dividing all scores by the average score during the Green condition.

The raw cognitive scores for each domain were normalized to the conventional condition and modeled by study day controlling for participant (Table 1.5). The repeat simulation of the Green+ day (Day 6), which was added to the study as a quality control measure, showed similar cognitive function scores: p-values for the null hypothesis of no difference between the two days ranging from 0.27 for Strategy (normalized scores of 3.77 and 3.98, respectively) to 0.73 for Crisis Response (normalized scores of 2.35 and 2.27). The Green+ condition had statistically significantly higher cognitive function scores than the Conventional condition in all domains ($p<0.0001$). The Green condition had higher scores than the Conventional condition in all domains, five of which were statistically significant.

Participants scored higher on the Green+ days than the Green day in eight of nine domains, resulting in a 25% increase in scores on average when outdoor air ventilation rates were increased. Cognitive scores were 20% higher on the Green+ days than the moderate CO_2 day when CO_2 levels were higher (p-value < 0.0001) and 5% higher on the moderate CO_2 day than the Green day when outdoor air ventilation was reduced (p-value = 0.12). These estimates and p-values were produced by rerunning the "average" model in Table 1.5 with the Green condition as the reference category (data not shown).

The model of the average scores in Table 1.5 has a high R^2 value of 0.81 indicating that a significant amount of the variability in cognitive scores is explained by these indoor environment test conditions, leaving only 19% of the variability to be explained by all other potential intra-personal drivers of cognitive function such as diet, previous night sleep quality, and mood. For the specific domains of cognitive function, the R^2 range from 0.03 to 0.79.

Table 1.5 Generalized additive mixed effect models testing the effect of IEQ condition and on cognitive scores, normalized to the "Conventional" condition, treating participant as a random intercept.

	Cognitive Domain: Estimate, [95% Confidence Interval], (p-value)									
Condition	Basic Activity Level	Applied Activity Level	Focused Activity Level	Task Orientation	Crisis Response	Information Seeking	Information Usage	Breadth of Approach	Strategy	Average
Green+	1.35	1.39	1.44	1.14	2.35	1.10	3.94	1.43	3.77	1.99
	[1.28,1.43]	[1.26,1.52]	[1.27,1.62]	[1.11,1.17]	[1.91,2.78]	[1.07,1.14]	[3.47,4.41]	[1.25,1.60]	[3.40,4.14]	[1.89,2.09]
	(<0.0001)	(<0.0001)	(<0.0001)	(<0.0001)	(<0.0001)	(<0.0001)	(<0.0001)	(<0.0001)	(<0.0001)	(<0.0001)
Moderate CO_2	1.20	1.08	1.68	1.05	2.05	1.11	2.61	1.29	3.17	1.69
	[1.13,1.27]	[0.95,1.21]	[1.51,1.85]	[1.02,1.08]	[1.63,2.48]	[1.08,1.15]	[2.15,3.07]	[1.12,1.46]	[2.81,3.53]	[1.59,1.79]
	(<0.0001)	(0.23)	(<0.0001)	(0.0009)	(<0.0001)	(0.61)	(<0.0001)	(0.0013)	(<0.0001)	(<0.0001)
High CO_2	0.91	0.88	0.85	1.00	1.33	1.08	1.01	0.98	0.83	0.99
	[0.84,0.98]	[0.75,1.01]	[0.68,1.02]	[0.97,1.03]	[0.90,1.75]	[1.05,1.12]	[0.55,1.48]	[0.81,1.15]	[0.47,1.19]	[0.89,1.09]
	(0.015)	(0.081)	(0.087)	(0.76)	(0.14)	(0.35)	(<0.0001)	(0.78)	(0.36)	(0.78)
Green	1.14	1.04	1.51	1.03	1.97	1.09	2.72	1.21	2.83	1.61
	[1.06,1.21]	[0.91,1.18]	[1.34,1.68]	[1.00,1.06]	[1.54,2.40]	[1.05,1.12]	[2.26,3.19]	[1.04,1.38]	[2.46,3.19]	[1.51,1.71]
	(0.0003)	(0.51)	(<0.0001)	(0.065)	(<0.0001)	(0.45)	(<0.0001)	(0.018)	(<0.0001)	(<0.0001)
Conventional[a]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Green+	1.37	1.33	1.52	1.15	2.27	1.11	4.04	1.50	3.98	2.03
	[1.30,1.44]	[1.20,1.46]	[1.35,1.69]	[1.12,1.19]	[1.85,2.69]	[1.08,1.15]	[3.58,4.51]	[1.33,1.67]	[3.62,4.34]	[1.93,2.13]
	(<0.0001)	(<0.0001)	(<0.0001)	(<0.0001)	(<0.0001)	(<0.0001)	(<0.0001)	(<0.0001)	(<0.0001)	(<0.0001)
R^2	0.34	0.17	0.33	0.03	0.28	0.06	0.69	0.27	0.79	0.81

[a] Reference

1.3.2 Carbon Dioxide and Cognitive Function

The effect of CO_2 on cognitive function scores, while holding all other parameters constant, is depicted in Figure 1.2. Because the air in each room was not completely mixed, there was some variability in CO_2 levels between cubicles. Each line represents the change in an individual's CO_2 exposure and cognitive scores from one condition to the next, normalized by the average CO_2 exposure across all participants during the Green+ conditions. For seven of the nine cognitive function domains, average cognitive scores decreased at each higher level of CO_2 (Table 1.5). Cognitive function scores were 15% lower for the moderate CO_2 day (~945 ppm) and 50% lower on the day with CO_2 concentrations around 1400 ppm than on the two Green+ days (Table 1.5, dividing the average Green+ estimate by the moderate CO_2 and high CO_2 estimate respectively). The exposure-response between CO_2 and cognitive function is approximately linear across the concentrations used in this study; however, whether the largest difference in scores is between the Green+ conditions and the moderate CO_2 condition or the moderate CO_2 condition and the high CO_2 condition depends on the domain (Figure 1.2).

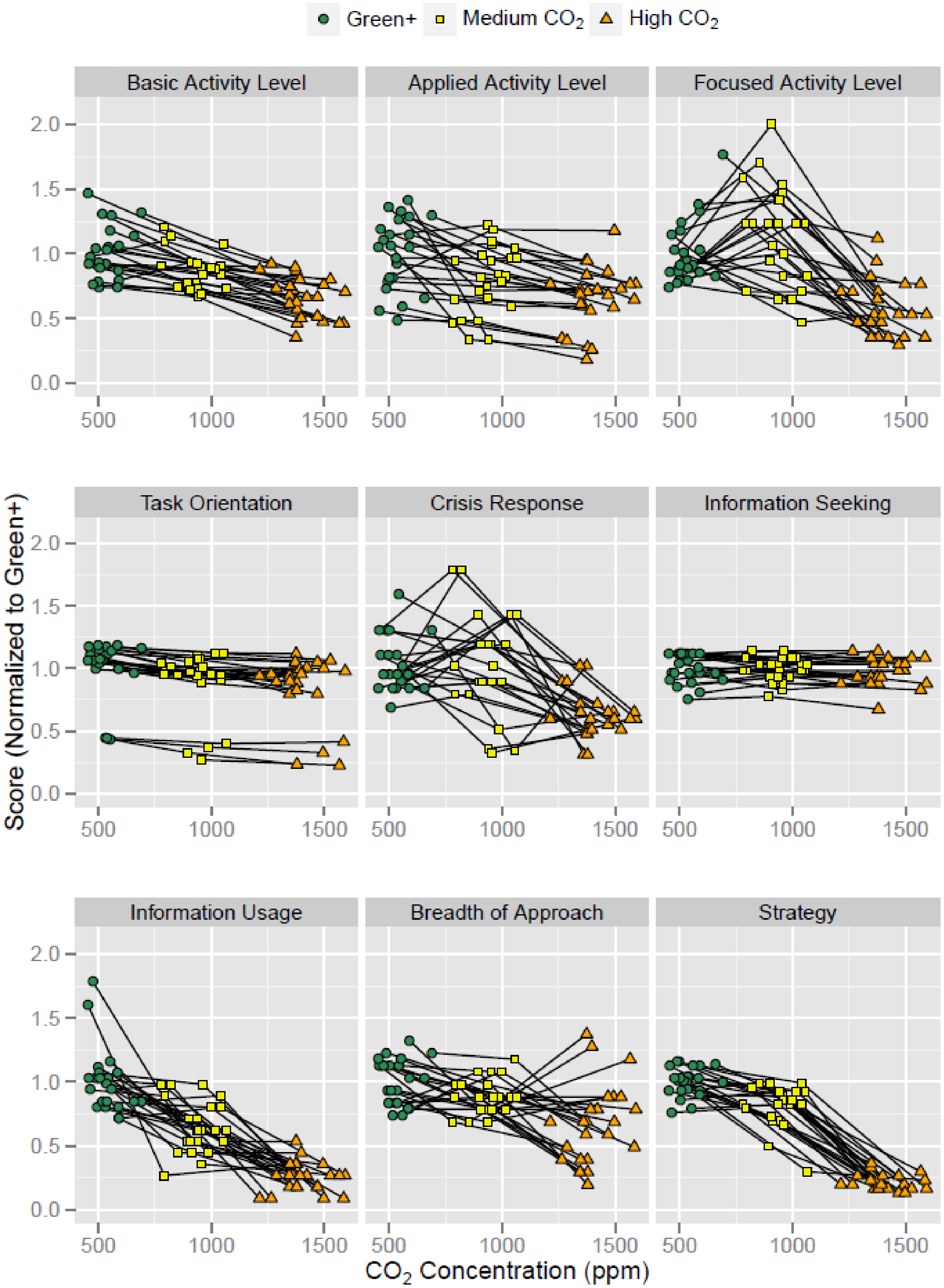

Figure 1.2 Cognitive function scores by domain and participant, and corresponding carbon dioxide concentration in their cubicle. Each line represents the change in an individual's CO_2 exposure and cognitive scores from one condition to the next, normalized by the average CO_2 exposure across all participants during the Green+ conditions.

Ventilation rate, CO_2, and TVOCs were modeled separately from study day to capture the independent effect of each factor on cognitive function scores, averaged across all domains. A statistically significant increase in scores was associated with ventilation rate, CO_2 and TVOCs ($p<0.0001$ for all three parameters). On average, a 400 ppm increase in CO_2 was associated with a 21% decrease, a 20 CFM increase in outdoor air per person was associated with an 18% increase, and a 500 $\mu g/m^3$ increase in TVOCs was associated with a 13% decrease in a typical participant's cognitive scores across all domains after adjusting for participant (data not shown). While other environmental variables were not experimentally modified, some did vary over the course of the study (Table 1.2). While there was a high degree of consistency in IEQ between the two rooms, ozone was significantly higher in one of the chambers on the Green day. Cognitive scores were 4% higher in the room with high ozone on this day, after accounting for baseline cognitive performance in the two rooms. These IEQ parameters were added to the model with the experimentally controlled variables and were not found to be significantly associated with cognitive function at the 0.05 significance level.

1.4 Discussion

1.4.1 Green Buildings and Health

We found a significant increase in cognitive function scores when people spent a full day in a Green building compared to an environment designed to simulate a Conventional building by elevating VOC concentrations. The study was designed to represent typical conditions observed in many buildings; we did not include extreme exposures or choose uncommon VOC sources. Further, we selected our target levels of VOCs, ventilation rates and CO_2 to be above and below the standards in LEED®, ASHRAE, and EPA BASE study in order to evaluate how these common standards and guidelines perform (USGBC 2014, ASHRAE 2013b, USEPA 1998). Our findings indicate that there may be benefits to meeting the LEED® VOC guideline of 500 $\mu g/m^3$ and enhancing ventilation rates beyond the minimum requirement under ASHRAE.

The "Conventional" building simulation parameters in our study were based on the USEPA BASE study, which plausibly represent the upper end of performance for "typical" buildings in the U.S. in the 1990s because the owners were willing to participate in the study, introducing potential self-selection bias, and larger, "non-problem" buildings were preferentially recruited (Persily 2004). Therefore, the extent to which BASE buildings represent typical conventional buildings is unknown. Our findings show impacts above the 95th percentile of CO_2 (945 ppm) and the mean VOC concentration in the BASE study (450 $\mu g/m^3$); however, a larger proportion of the buildings in the BASE study would likely exceed these targets if "problem" buildings were included in the recruitment process.

The VOC levels on the Conventional and Green/Green+ days straddle both the LEED® TVOC guidance concentration of 500 $\mu g/m^3$ and the BASE mean concentration of 450 $\mu g/m^3$. The common VOC sources that were added to the rooms during the Conventional building day led to increases in a range of VOCs. Previous testing with the SMS tool showed that two hours of painting, which exposed participants to VOCs, was associated with reductions in 3 of the 5 domains investigated (Satish et al., 2013). The lower TVOC concentrations (yet larger number of sources) in this study were associated with statistically significant decrements in decision-making performance in 5 of the 9 domains.

1.4.2 Carbon Dioxide and Ventilation

Carbon dioxide concentration in indoor environments has long been used as an indicator of ventilation and a proxy for indoor air quality (ASHRAE 2013). However, this conventional thinking is being challenged as the evidence mounts for CO_2 as a direct pollutant, not just a marker for other pollutants (Satish et al. 2012). We found statistically significant declines in cognitive function scores when CO_2 concentrations were increased to levels that are common in indoor spaces (approximately 950 ppm). In fact, this level of CO_2 is considered acceptable because it would satisfy ASHRAE's ventilation rate guidance for acceptable indoor air quality. Larger differences were seen when CO_2 was raised to 1400 ppm.

Satish et al. used the SMS tool to test the effect of CO_2 exposures on the cognitive function of 22 participants, using a controlled chamber and injection of ultra-pure CO_2 (Satish et al. 2012). They reported impacts on 7 of 9 cognitive function domains with increasing CO_2 concentrations. The SMS tool was also used to test the relationship between ventilation rate and cognitive function among 16 participants (Maddalena et al. 2014). Participants scored significantly lower on 8 of 9 domains at low ventilation rates (12.5 cfm of outdoor air/person). In contrast to our current study, these studies had 1) a single experimental parameter; 2) half-day or shorter exposures; 3) multiple experimental conditions per day; 4) atypical exposure targets (2500 ppm of CO_2 and 12.5 cfm outdoor air/person); and 5) primarily students and college-age adults. Despite these differences, our study found similar changes in cognitive scores from a unit change in CO_2 or outdoor air ventilation. Associations were consistent a) in all three study populations, indicating that knowledge workers and students are equally impacted by CO_2 and outdoor air ventilation, and b) at different exposure durations, indicating that even short exposures are associated with cognitive function. Given the similarities in findings, there may not be a desensitization or compensatory response from prolonged exposure. More research is necessary to investigate the presence or lack of these responses.

The CO_2 exposure levels used in this study are also comparable to those seen in a variety of indoor locations. Assessment of public housing units in Boston found median CO_2 levels to be 809 ppm in conventional apartments and 1204 ppm in the newly constructed LEED® platinum apartments (Colton et al. 2014). Corsi et al. (2002) reported CO_2 concentrations > 1000 ppm in 66% of 120 classrooms in Texas, and Shendell et al. (2004) measured CO_2 concentrations >1000 ppm in 45% of 435 classrooms in Washington and Idaho, and reported that higher CO_2 concentrations were associated with increases in student absences.

1.4.3 Strengths and Limitations

The study design has several notable strengths. These include: repeat measures of cognitive function on the same individual for control of between-subject variability, characterization of the TIEQ Lab for potential environmental confounders, repeat testing of the same condition nine days apart on different days of the week, mid-week testing to avoid potential Monday/Friday bias, participants and cognitive function analysts blinded to test condition, and the use of an objective measure of cognitive function.

The SMS tool is an objective assessment tool, unlike self-reported metrics, and thus less susceptible to the participant's environmental perceptions. Extensive work has been dedicated to testing the validity of the SMS software; correlations between scores on these tests and other measures of productivity such as income at age and job level at age exceed 0.6 (Streufert et al. 1988). The correlations are stronger with the more strategic domains, such as strategy, information usage, and crisis response, than domains pertaining to activity, such as information search and activity level. The domains that were impacted the most by the exposures in this study are the same ones that are the most closely related with other measures of productivity (Streufert et al. 1988). Lastly, the close agreement in scores on the two Green+

conditions suggests that a) the study is internally valid, b) there are no learning effects associated with the test, and c) day of the week (Tuesday v. Thursday) is not a potential confounding variable.

The potential for confounding or effect modification by parameters measured or otherwise is reduced by the use of the controlled environment and repeated measures on each participant. By testing on subsequent days, it is possible that effects from one condition were reflected in the scores on the next day. The environmental factors that were not experimentally modified exhibited some variability due to changes in outdoor conditions and participant behavior. In particular, ozone levels fluctuated significantly between some IEQ conditions (Table 1.2). Environmental factors other than outdoor air ventilation, CO_2 and VOCs were not statistically significant predictors of cognitive scores, but this does not rule out the possibility of uncontrolled confounding by these factors. The environmental conditions on each of the study days met design criteria. During one day (Day 4), CO_2 levels were lower in the morning than the afternoon, which influenced the reported mean concentration. The CO_2 levels on this day were similar to the moderate CO_2 and Conventional conditions (Day 5) during the time leading up to and during the cognitive test (926 ppm from 2-5p.m.). This study used a controlled environment to individually control certain contaminants. Assessments in actual office environments are important to confirm the findings in a non-controlled setting.

1.5 Conclusion

Office workers had significantly improved cognitive function scores when working in Green and Green+ environments compared to a Conventional one. Exposure to CO_2 and VOCs at levels found in Conventional office buildings was associated with lower cognitive scores compared to levels in a Green building. Using low emitting materials, which is common practice in Green buildings, reduces in-office VOC exposures. Increasing the supply of outdoor air not only lowers exposures to CO_2 and VOCs, but also exposure to other indoor contaminants. Green building design that optimizes employee productivity and energy usage will require adopting energy efficient systems and informed operating practices to maximize the benefit to human health while minimizing energy consumption. This study was designed to reflect indoor office environments in which large numbers of the population work every day. These exposures should be investigated in other indoor environments, such as homes, schools and airplanes, where decrements in cognitive function and decision-making could have significant impacts on productivity, learning and safety.

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CHAPTER 2 - Economic, Environmental and Health Implications of Enhanced Ventilation in Office Buildings

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Abstract

Introduction: Current building ventilation standards are based on acceptable minimums. Three decades of research demonstrates the human health benefits of increased ventilation above these minimums. Recent research also shows the benefits on human decision-making performance in office workers, which translates to increased productivity. However, adoption of enhanced ventilation strategies is lagging. We sought to evaluate two of the perceived potential barriers to more widespread adoption—Economic and environmental costs.

Methods: We estimated the energy consumption and associated per building occupant costs for office buildings in seven U.S. cities, representing different climate zones for three ventilation scenarios (standard practice (20 cfm/person), 30% enhanced ventilation, and 40 cfm/person) and four different heating, ventilation and air conditioning (HVAC) system strategies (Variable Air Volume (VAV) with reheat and a Fan Coil Unit (FCU), both with and without an energy recovery ventilator). We also estimated emissions of greenhouse gases associated with this increased energy usage, and, for comparison, converted this to the equivalent number of vehicles using greenhouse gas equivalencies. Lastly, we paired results from our previous research on cognitive function and ventilation with labor statistics to estimate the economic benefit of increased productivity associated with increasing ventilation rates.

Results: Doubling the ventilation rate from the American Society of Heating, Refrigeration and Air-Conditioning Engineers minimum cost less than $40 per person per year in all climate zones investigated. Using an energy recovery ventilation system significantly reduced energy costs, and in some scenarios led to a net savings. At the highest ventilation rate, adding an ERV essentially neutralized the environmental impact of enhanced ventilation (0.03 additional cars on the road per building across all cities). The same change in ventilation improved the performance of workers by 8%, equivalent to a $6500 increase in employee productivity each year. Reduced absenteeism and improved health are also seen with enhanced ventilation.

Conclusions: The health benefits associated with enhanced ventilation rates far exceed the per-person energy costs relative to salary costs. Environmental impacts can be mitigated at regional, building, and individual-level scales through the transition to renewable energy sources, adoption of energy efficient systems and ventilation strategies, and promotion of other sustainable policies.

Keywords: green buildings; energy and environmental costs; health; productivity

2.1 Introduction

Buildings account for 41% of US energy consumption, with nearly half of that energy usage coming from the commercial sector [1]. In office buildings, over half of the end-use energy expenditures are attributable to heating, ventilating, and cooling [2]. The environmental impact of these energy expenditures has been well documented; greenhouse gases emitted during power production are associated with climate change impacts including rising sea level, extreme temperatures, and more frequent weather events [3,4]. Emissions of sulfur dioxide (SO_2) contribute to acid rain, which can damage sensitive ecosystems [5]. More important, however, are the downstream human health effects related to these environmental impacts. Elevated temperatures and droughts will increase the likelihood of heat-related illness and mortality [6]. Extreme weather effects also pose health and economic risks, especially in developing regions [7]. Emissions from power plants also have several direct health effects: (1) exposure to particulate matter, in particular SO_2, increases the risk of respiratory and cardiovascular disease and (2) nitrogen oxides (NO_x) cause airway inflammation and respiratory symptoms, especially in asthmatics [8,9].

At the building level, buildings managers are incentivized to reduce costs, which often is achieved by reducing ventilation rates. Similar incentives are not set for optimizing the health performance of buildings as occupant health is more difficult to characterize. Further, building managers tend to overestimate the energy costs related to ventilation. When asked the cost per occupant to double the ventilation rate from 20 cfm/person to 40 cfm/person and improve filtration from a minimum efficiency reporting value (MERV) 6 to a MERV 11 filter, building managers reported a perceived cost per occupant of $100 while the modeled estimates were consistently below $32 per occupant for all climate zones [10]. Consultants, tenants and owners also overestimated the costs of improved ventilation per occupant at \$60, \$115, and \$80, respectively. Owners and building managers believe that tenants do not consider indoor air quality (IAQ) when leasing a space: 58% of respondents reported that 20% or less of their tenants take IAQ into consideration [10]. As a result, the cost of energy is often prioritized over IAQ and minimum required ventilation rates are met.

The guidelines that buildings operate under are by definition minimally acceptable. ASHRAE defined its original ventilation Standard 62 as “the minimum and recommended air quantities for the preservation of the occupants’ health, safety and well-being” [11]. In the initial standard, the minimum ventilation requirement was 10 cfm/person. Sick building syndrome (SBS) was first reported around the time of early standard adoption and coincided with improved sealing of building envelopes; occupants of poor performing buildings started reporting a wide range of symptoms including respiratory irritation, allergies, and headaches, which were later linked to the buildup of biological and chemical pollutants in the indoor environment [12].

In response, ASHRAE has since increased minimum acceptable ventilation rates under Standard 62.1 to approximately 20 cfm/person depending on the size and occupancy of the rooms within the building [13]. SBS symptoms and productivity losses have still been observed at this ventilation rate compared to higher ventilation rates. The prevalence of many SBS symptoms, such as throat/mouth dryness, feeling generally bad or good, and difficultly thinking, are reduced at ventilation rates above 20 cfm/person [14]. Recent research by our team also show cognitive improvements at 40 cfm/person compared to 20 cfm/person [15]. Absenteeism, productivity losses, and healthcare costs due to ventilation are estimated to have annual economic impacts in the hundreds of billions of dollars in the U.S. [16]. According to this analysis, a 5% change in productivity is equivalent to $125 billion in economic value based on the annual GNP of U.S. office workers, which is equivalent to $186 billion in 2015 dollars.

Sustainable or “green” design has sought improve occupant wellbeing in buildings while also reducing their environmental footprint. In 1990, Building Research Establishment Environmental Assessment Methodology (BREEAM) was founded as an international certification agency for green buildings. Three years later the Leadership in Energy and Environmental Design (LEED) rating system was established with a similar concept, focusing on U.S. buildings. Both agencies utilize design credits, which are subdivided into various sections, such as energy, water, and waste. Within each section there are required credits, which typically conform to local standards and guideline, and optional credits. To achieve a certain ranking, designers and architects can choose which optional credits to pursue. For example, LEED offers optional credits for both energy efficiency and increasing ventilation by 30%. In practice, the energy efficiency credits are preferentially chosen: only 40% of the new construction and 23% of the existing buildings rated under LEED v2009 obtained the enhanced ventilation credit. With advances in HVAC equipment such as energy recovery ventilators (ERVs), which significantly reduce energy use, it is possible to obtain credits for both energy efficiency and enhanced ventilation.

There is currently a lack of consensus about whether the energy costs and environmental impacts of increased ventilation outweigh the resulting health and productivity benefits. The burden of all four of these factors is estimated in a standard office building at 20 cfm/person (9.4 l/s/p), 27.6 cfm/person (13.0 l/s/p) (the ventilation rate to obtain the enhanced ventilation credit with LEED), and 40 cfm/person (18.8 l/s/p). We also test the effect of adding ERV to the higher ventilation scenarios. We then compare these scenarios to place the energy, environmental, health, and productivity factors into context.

2.2 Methods

2.2.1. Estimating Economic Costs of Enhanced Ventilation

Energy cost consequences are a function of local climate; local utility prices; building type, use and design; local building code requirements; ventilation rate; and HVAC system design. We used Carrier's Hourly Analysis Program (HAP) to first calculate the annual energy consumption in kWh for fans, motors, pumps and chillers, plus natural gas in MCF (the volume of 1000 cubic feet (cf) of natural gas) for the hot water boilers for a range of scenarios, described in the following paragraphs. Energy use data was converted to kBtu/year (thousand Btu/year) so electric and gas consumption could be combined into a single value. Second, we estimated the annual per building occupant energy costs, in US dollars, associated with these energy costs based on local utility prices (Table 2.1) [17].

Table 2.1 Climate and fuel costs used for model inputs. Electricity generation fuel mix used for environmental impact assessment.

City Used in Study	Climate Zone	Summer Design		Winter Design	EIA State Average Price	
		Dry-Bulb	Coincident Wet-Bulb	Dry-Bulb	Electricity (\$/kWh)	Gas (\$/1000 ft^{3})
Austin, TX	2A–Hot, Humid	100 F (38 °C)	74 F (23 °C)	28 F (−2 °C)	0.0830	7.24
Charlotte, NC	3A–Warm, Humid	94 F (34 °C)	74 F (23 °C)	21 F (−6 °C)	0.0873	8.62
San Francisco, CA	3C–Warm, Marine	83 F (28 °C)	63 F (17 °C)	39 F (4 °C)	0.1457	7.05
Baltimore, MD	4A–Mixed, Humid	94 F (34 °C)	75 F (24 °C)	14 F (−10 °C)	0.1070	10.00
Albuquerque, NM	4B–Mixed, Dry	95 F (35 °C)	60 F (16 °C)	18 F (−8 °C)	0.0987	6.69
Boston, MA	5A–Cool, Humid	91 F (33 °C)	73 F (23 °C)	8 F (−13 °C)	0.1451	10.68
Boise, ID	5B–Cool, Dry	99 F (37 °C)	64 F (18 °C)	9 F (−13 °C)	0.0740	7.35

City Used in Study	Energy Provider	Fuel Mix (%)					
		Renewables	Hydro	Nuclear	Oil	Gas	Coal
Austin, TX	Austin Energy	7	0.2	12	0.8	45	34.8
Charlotte, NC	Duke Energy Carolinas	2	1.5	38.2	0.5	11.7	45.7
San Francisco, CA	City and County of SF	10.4	15.2	15.2	1.2	50.4	7.1
Baltimore, MD	Baltimore Gas and Electric	2	1	39.9	0.5	20.6	35.3
Albuquerque, NM	PNM Resource Inc.	3.4	6.2	17.5	0.1	33.4	39.5
Boston, MA	NSTAR	6.1	5.9	29.5	0.8	45.3	10.8
Boise, ID	Idaho Power Co.	6.8	43.6	3.4	0.3	14.3	31.3

For local climate, we modeled costs for seven U.S. cities that represent different climate zones. The climates ranged from hot/humid locales (Austin, TX, USA) to cool/dry locales (Boise, ID, USA), as seen in the dry-bulb and wet-bulb temperatures in these regions (Table 2.1). For building type, we were primarily interested in office buildings and selected the Department of Energy Medium Office Prototype as our template building [18]. This building type assumes a 53,661 sqft (4985 m^{2}) floor area, three-story building with 268 occupants (200 sqft/person). We used ASHRAE 90.1-2010 Prescriptive Construction (code minimum) for construction type, which prescribes wall, roof and window assemblies, and light power density. For utility costs, we utilized the state average utility prices for each city in the model, using the Energy Information Administration electric and gas prices as of the date of this study.

For ventilation rate we modeled three rates, starting with the baseline condition as the ASHRAE Standard 62–2001 default minimum ventilation rate of 20 cfm/person of outdoor air. The 2001 edition of the standard was chosen for the baseline to be representative of existing building stock. Second, we calculated the outdoor airflow rate for the template building to obtain the LEED enhanced ventilation credit. The credit requires a ventilation rate 30% higher than ASHRAE Standard 62.1-2010, which is dependent on the occupancy and floor area of the building. For the template building this yields an approximate ventilation rate of 27.6 cfm/person. Last, we modeled the costs of enhancing ventilation to a doubling of the ASHRAE Standard 62-2001 minimum (40 cfm/person) based on findings of significant health and productivity benefits reported for this ventilation rate.

For the HVAC strategy, we used two air distribution systems that are typical for office buildings—variable air volume (VAV) and fan coil unit (FCU) systems. Both VAV and FCU are mature technologies with equal adoption by new and old buildings. For each system, we also evaluated the energy costs with and without an ERV to determine if an ERV mitigates the effects of increased ventilation rates.

A schematic of a typical VAV reheat system is provided in the Supplemental Information (Figure 2.1). This is a common HVAC application for offices that use a central station VAV air handling unit (AHU). Cooling is supplied to the AHU by an air-cooled chiller plant and heating is provided by a hot-water plant. Even in existing buildings, this HVAC system is capable of being modified to adjust the ventilation rate to 40 cfm/person, though an increase in chiller, boiler and/or AHU capacity may be required.

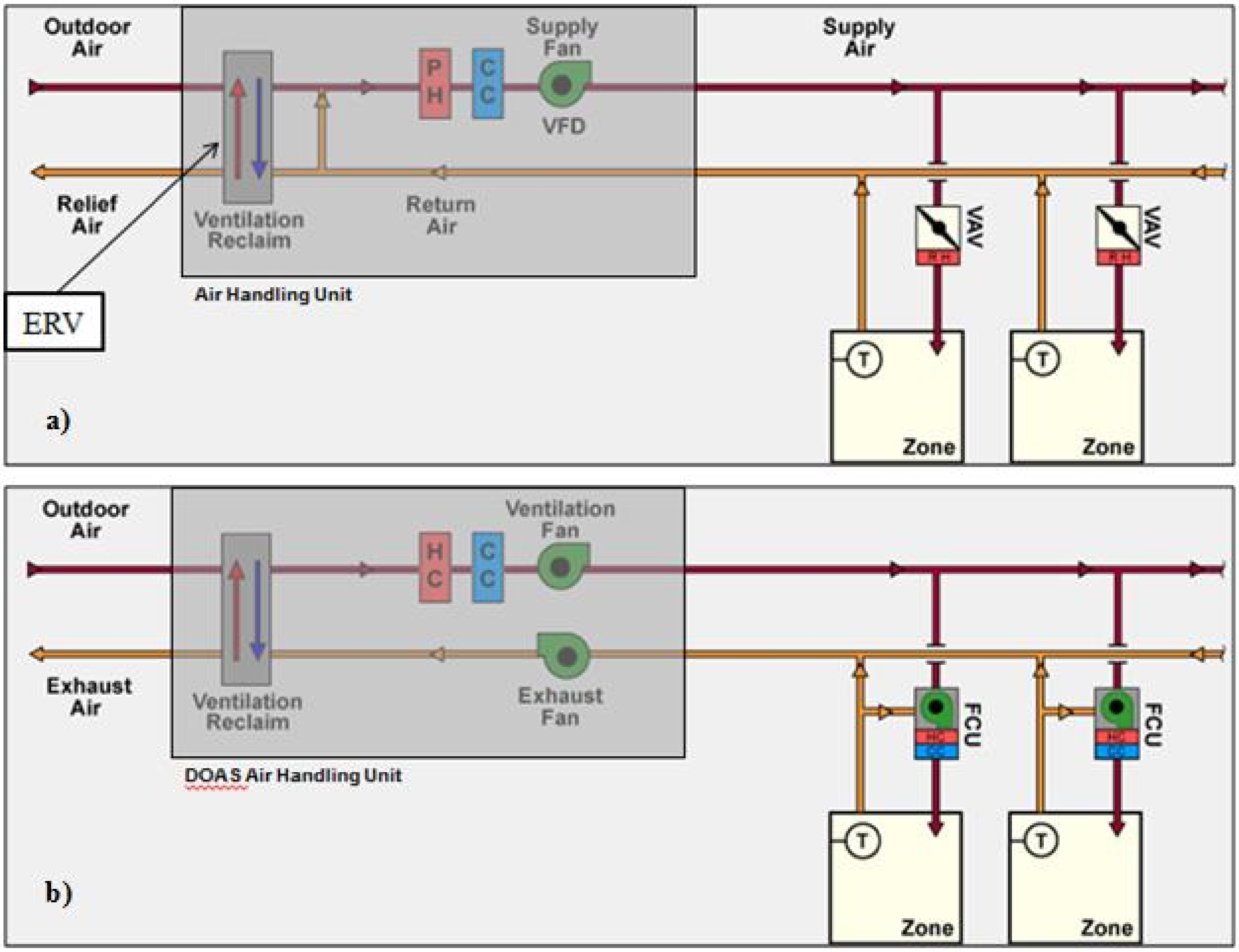

Figure 2.1 Schematics of a) a variable air volume ventilation system and b) a fan coil unit ventilation system.

The second system we evaluated is 4-pipe fan coils (FCU) with a dedicated outdoor air system (DOAS) (Figure 2.1). This HVAC system is also a common application for office buildings. The DOAS conditions outdoor ventilation air and supplies it to the FCUs, which provide cooling and heating to rooms in the building. Similar to the VAV-reheat system, cooling is provided by an air-cooled chiller plant and heating is provided by a hot water plant. A limitation of the DOAS system is that it is designed for a certain ventilation rate (e.g., 20 cfm/person) and cannot readily accommodate significantly increased ventilation rates. The FCU system also has larger baseline energy costs compared to the VAV system for this building case study.

An ERV is a device that utilizes the energy in exhaust air from the building to heat or cool outdoor ventilation air entering the building. During heating seasons the exhaust air preheats and humidifies outside air, while the opposite happens during cooling seasons. This transfer of both sensible and latent heat saves energy that otherwise would be exhausted from the building, which reduces the energy that needs to be supplied by other elements of the HVAC system to maintain a specific set temperature and humidity.

For all scenarios, thermostat set points of 75 °F (23.9 °C) for cooling and 70 °F (21.1 °C) for heating with nighttime setbacks to 80 °F (26.7 °C) for cooling and 65 °F (18.3 °C) for heating. Humidity was not actively controlled in the model, but typically fell in the 40%–50% range for variable air volume (VAV) systems and 45%–60% range for fan coil unit (FCU) systems. The potential influence of this variability in humidity on cognitive function was not investigated.

2.2.2. Estimating Environmental Effects of Enhanced Ventilation

We used the energy usage estimates in the first part of the analysis described previously and the U.S. Environmental Protection Agency's (EPA) Power Profiler to calculate the emissions for each scenario for the following air pollutants: nitrogen oxides (NO_x), sulfur dioxide (SO_2), and carbon dioxide (CO_2). We used the most centralized zip code and most prevalent energy provider in each of the seven modeled cities. To provide another point of comparison, we also converted the energy usage information into emission equivalencies using EPA's Greenhouse Gas Equivalencies Calculator.

We estimated the emissions equivalent for the building energy consumption in terms of passenger vehicles per year. Passenger vehicles are defined as 2-axle 4-tire vehicles, including passenger cars, vans, pickup trucks, and sport/utility vehicles. In 2011, the weighted average combined fuel economy of cars and light trucks combined was 21.4 miles per gallon (9.1 km/L) [19]. The average vehicle miles traveled in 2011 was 11,318 miles (18,215 km) per year. In 2011, the ratio of CO_2 emissions to total greenhouse gas emissions (including carbon dioxide, methane, and nitrous oxide, all expressed as carbon dioxide equivalents) for passenger vehicles was 0.988 [20]. The amount of carbon dioxide emitted per gallon of motor gasoline burned is 8.89×10^{-3} metric tons [21].

2.2.3. Estimating Health Benefits of Enhanced Ventilation

In a previous study of ventilation and cognitive function by our study team, 24 participants were exposed to 20 and 40 cfm of outdoor air per person on different study days [15]. At the end of each study day, they completed the Strategic Management Simulation (SMS) cognitive test, which measures decision-making performance across nine domains: basic, applied and focused activity level, task orientation, crisis response, information seeking and usage, breadth of approach and strategy. In this current paper, we used the participants' scores from our previous study and plotted them against normative data of 70,000 previous SMS test takers to see the percentile shift from one ventilation condition to the next (Figure 2.2).

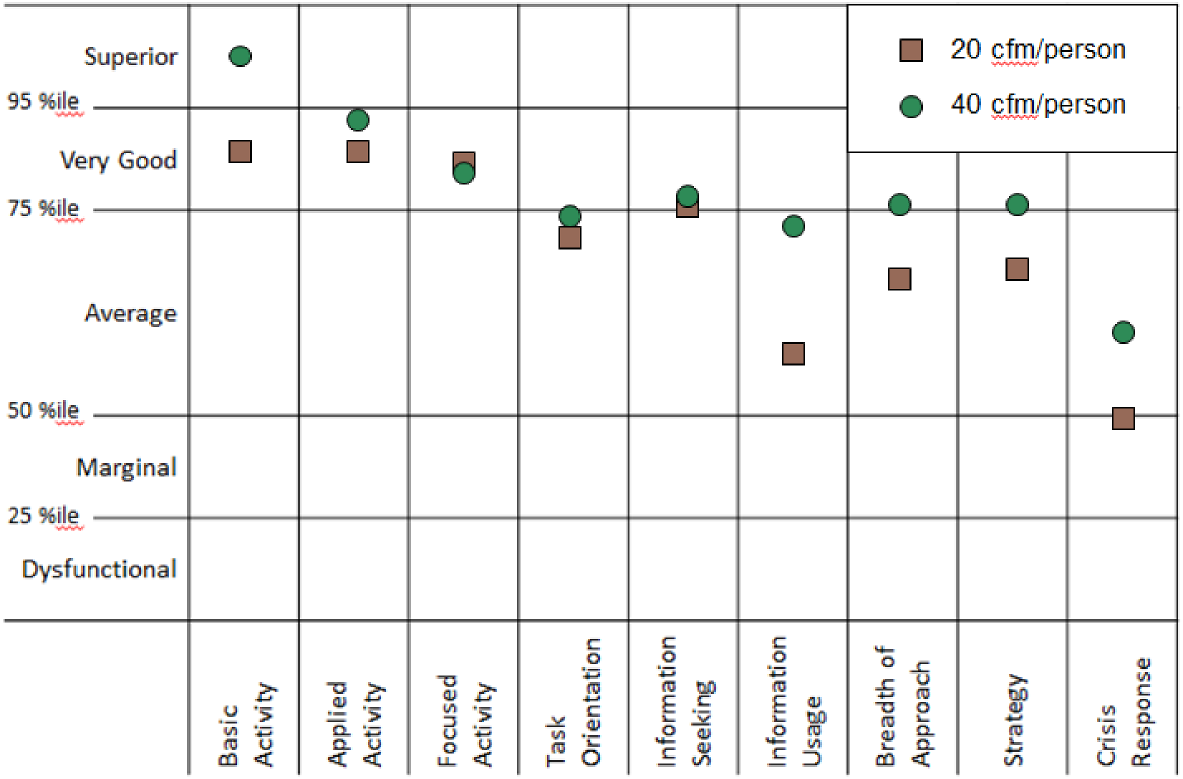

Figure 2.2 Average cognitive performance on the SMS tool of 24 participants in a green building at 20 and 40 cfm/person of outdoor air relative to normative data from ~70,000 people.

Data on salaries for various occupations was obtained from the Bureau of Labor Statistics (BLS). The 10th, 25th, 50th, 75th and 90th percentile salaries for management, business and financial operations, office and administrative support, computer and mathematical, architecture and engineering, legal, and sales occupations from May 2014 were used for analyses [22]. These occupation groups were selected to represent the U.S. office workforce and accounts for 57 million of the 135 million employments listed by BLS. Using averages weighted by the number of employments in each occupation group, mean salaries were computed for each percentile. The 90th percentile was missing for management and legal occupations so it was excluded from subsequent analyses. These salaries were plotted and regressed using an exponential function (Figure 2.3).

2.3 Results

2.3.1. Energy Costs and Environmental Effects of Enhanced Ventilation

Energy costs are influenced by factors such as local climate, local fuel prices, building type, use, and design, ventilation rate and HVAC system. The modeled energy costs of enhanced ventilation are summarized in Table 2.2. Increasing ventilation rates 30% above the ASHRAE standard only costs $15 per occupant per year in Boston (cool, humid) and only $4–$7 per occupant per year in Albuquerque (mixed, dry) (results for other cities across the U.S. fall within this range). For a doubling of this minimum standard to 40 cfm/person, the costs for Boston and Albuquerque are $40 and $20 per occupant per year, respectively.

Adding an ERV to the system largely mitigates the energy costs of increasing ventilation. The ERV reduces the anticipated increase in energy costs by 60% when increasing ventilation to 40 cfm/person. At 30% above the ASHRAE standard, the ERV actually lead to cost reductions in three of the seven cities compared to the 20 cfm/person condition for VAV, and seven of seven for FCU (Table 2.2). San Francisco is a notable exception. San Francisco has moderate year-round temperatures. When an ERV is added, fan energy increases because fans must work harder to overcome the resistance to air flow through the ERV. In most locations this fan energy increase is offset by larger reductions in cooling and heating energy. For San Francisco, which also has high electricity costs compared to gas costs, the cooling and heating energy reductions are smaller than the fan energy increase, so the net effect of adding an ERV is a small energy cost increase. The FCU system has higher baseline energy costs and is typically more susceptible to ventilation changes, but it also is more affected by the addition of an ERV. As ventilation rates increase with the ERV in place, the FCU energy costs approach that of the VAV system (Table S1).

Table 2.2 Change in energy cost per occupant per year compared to conventional.

Ventilation Rate	Austin	Charlotte	San Francisco	Baltimore	Albuquerque	Boston	Boise
Variable Air Volume							
20 cfm/person	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
27.6 cfm/person	$7.14	$7.29	$4.58	$10.42	$4.16	$12.03	$6.57
27.6 cfm/person + ERV	−$0.58	$0.42	$6.59	−$1.53	$3.77	−$0.82	$0.15
40 cfm/person	$23.07	$23.24	$15.73	$32.36	$14.34	$37.27	$20.78
40 cfm/person + ERV	$9.37	$10.55	$17.44	$11.21	$10.05	$14.06	$7.83
Fan Coil Unit							
20 cfm/person	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
27.6 cfm/person	$7.31	$8.63	$8.69	$12.35	$7.77	$15.19	$9.19
27.6 cfm/person + ERV	−$0.18	−$3.46	−$0.05	−$7.29	−$0.72	−$8.35	−$6.77
40 cfm/person	$19.20	$22.70	$22.94	$32.42	$20.41	$39.87	$24.13
40 cfm/person + ERV	$8.32	$5.18	$10.22	$4.01	$7.88	$5.81	$1.00

The environmental impacts follow a similar trajectory as the energy costs. The environmental footprint of buildings can be reduced in five of the cities by increasing ventilation by 30% while simultaneously adding an ERV (Table 2.3). The cities with the largest percentage increase in CO_2, SO_2 and NO_x emissions are the ones with the lowest baseline energy usage. For example, San Francisco uses 44% less energy during the 20 cfm/person scenario than other cities (Table S2). The large percentage increase in energy usage at 40 cfm/person actually amounts to a small increase in emissions. At 40 cfm/person, these emissions correspond to between 6.2 and 18.9 additional cars on the road per year. Adding an ERV significantly reduces the number of additional cars (Table 2.4). At the highest ventilation rate, adding an ERV essentially neutralizes the environmental impact of enhanced ventilation (0.03 additional cars on the road per building across all cities). This is driven primarily by the benefits seen in buildings with FCU systems.

Table 2.3 Percent increase in annual CO_2, SO_2 and NO_x emissions compared to conventional.

Ventilation Rate	Austin	Charlotte	San Francisco	Baltimore	Albuquerque	Boston	Boise
Variable Air Volume							
20 cfm/person	0%	0%	0%	0%	0%	0%	0%
27.6 cfm/person	14%	18%	25%	21%	17%	23%	21%
27.6 cfm/person + ERV	−1%	−2%	17%	−8%	0%	−10%	−7%
40 cfm/person	45%	55%	81%	63%	56%	67%	64%
40 cfm/person + ERV	17%	19%	61%	13%	18%	11%	13%
Fan Coil Unit							
20 cfm/person	0%	0%	0%	0%	0%	0%	0%
27.6 cfm/person	14%	16%	21%	18%	17%	19%	18%
27.6 cfm/person + ERV	−11%	−19%	−34%	−23%	−21%	−26%	−24%
40 cfm/person	36%	43%	56%	47%	44%	49%	46%
40 cfm/person + ERV	0%	−8%	−23%	−12%	−10%	−15%	−14%

These results are dependent on the fuel mix in each city. Cities that rely primarily on combustion-based energy sources have larger environmental impacts. For example, 58% of the energy in Boise comes from renewables, hydro, or nuclear sources, compared to only 27.6% in Albuquerque (Table 2.1). The template building in Boise under 20 cfm/person of ventilation contributes to 3% less CO_2 emissions than Albuquerque despite using 36% more energy on heating, cooling and ventilation each year.

Table 2.4 Number of additional cars per year on the road per building compared to conventional.

Ventilation Rate	Austin	Charlotte	San Francisco	Baltimore	Albuquerque	Boston	Boise
Variable Air Volume							
20 cfm/person	0.0	0.0	0.0	0.0	0.0	0.0	0.0
27.6 cfm/person	4.6	5.1	1.9	6.3	4.6	5.3	5.5
27.6 cfm/person + ERV	−0.5	−0.6	1.3	−2.5	0.0	−2.4	−1.7
40 cfm/person	14.5	15.7	6.2	18.8	14.6	15.6	16.7
40 cfm/person + ERV	5.6	5.6	4.7	3.9	4.7	2.6	3.5
Fan Coil Unit							
20 cfm/person	0.0	0.0	0.0	0.0	0.0	0.0	0.0
27.6 cfm/person	5.0	5.9	3.5	7.2	6.6	6.1	6.7
27.6 cfm/person + ERV	−4.0	−6.9	−5.3	−9.2	−8.2	−8.2	−9.1
40 cfm/person	13.2	15.5	9.0	18.9	17.3	15.8	17.6
40 cfm/person + ERV	0.1	−3.0	−3.6	−4.8	−4.0	−4.7	−5.2

2.3.2. Productivity Gains from Enhanced Ventilation

Figure 2.2 depicts the cognitive performance of the participants in our previous research on ventilation and decision-making performance [15]. These office workers performed above average in all domains. When ventilation was increased from 20 cfm/person to 40 cfm/person (the Green and Green + IEQ conditions respectively from that study), the participants increased from the 62nd percentile to the 70th percentile on average across all domains. Larger impacts were seen in basic activity, information usage, breadth of approach, strategy and crisis response than the other domains. When these percentiles were compared to the distribution of office worker salaries, they corresponded to a salary of $57,660 and $64,160 respectively, a difference of $6500 (Figure 2.3). When the occupational data was subsetted to management occupations, the difference in salaries at these percentiles was $15,500.

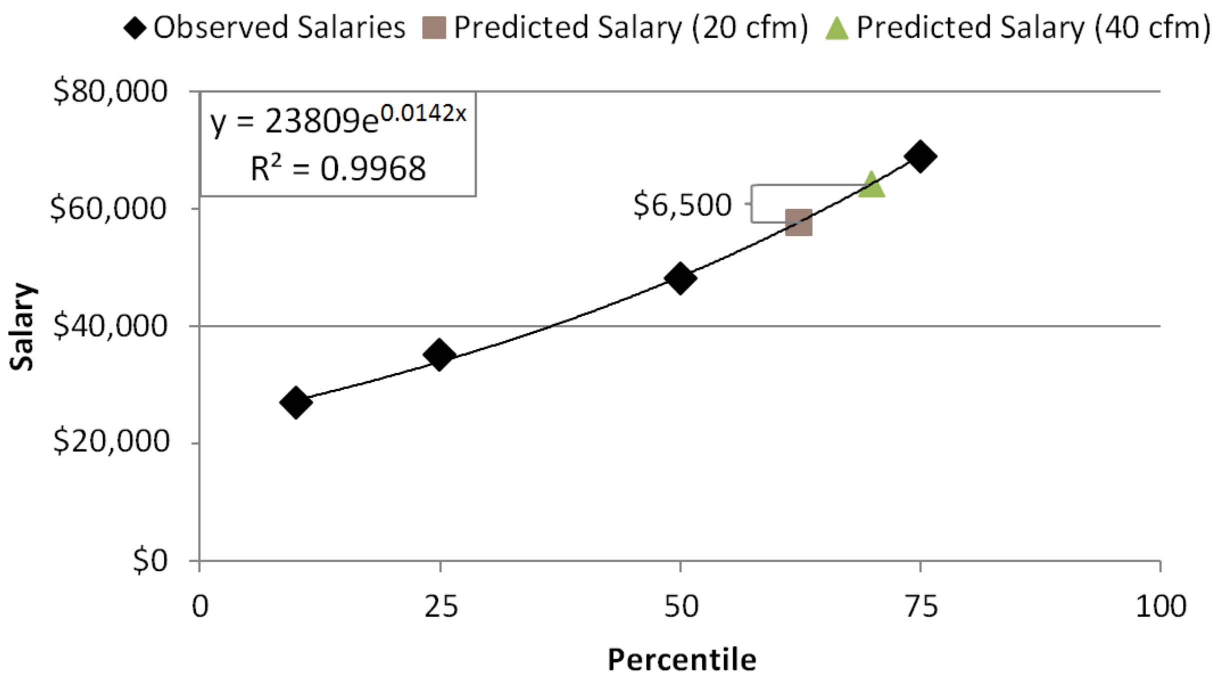

Figure 2.3 Observed salaries from the Bureau of Labor Statistics for common office occupations, regressed with an exponential function. This equation was used to interpolate salaries at the cognitive testing percentiles.

2.4 Discussion

Our motivation for this analysis stemmed from the observation that the public health benefits of enhanced ventilation have been researched and described for several decades, and our own recent research observed significant improvements in decision-making performance for office workers with enhanced ventilation, yet when we reviewed the prevalence of the selection of the enhanced ventilation credit in the leading green building rating system (LEED), we found that enhanced ventilation credit was pursued in only 40% of new buildings and 23% of existing buildings [15]. We hypothesized that one of the key barriers to more widespread adoption was the corresponding energy costs associated with increasing ventilation rates.

We found that the additional costs per occupant for enhancing ventilation rates were quite low; too low, in fact, to be a barrier for more widespread adoption. These costs are trivial (less than $40/year in the worst case scenario) when compared to the large improvements in cognitive function (greater than $6000/year) from increased ventilation. In our analysis, we examined the impact of including an ERV to offset energy usage and costs. As expected, energy usage costs dropped significantly with the use of these ERV systems in all U.S. cities. Most importantly, enhancing ventilation to 30% above the minimum, when paired with an ERV, led to cost savings in three of the seven cities in our model for VAV and seven of seven for FCU.

These findings are in agreement with Hamilton *et al.* that estimated annual costs from enhanced ventilation to be < $32 per person per year. In addition, they found cost perception may be a barrier to enhancing ventilation, despite the analysis that shows the actual costs to be low [10]. While the costs are low compared to productivity benefits, they do comprise a significant portion of building management budgets. The split incentive system, whereby building managers are responsible for energy costs while tenants are responsible for the cost of their employees, is a barrier to adoption as tenants cannot simply implement ventilation changes themselves. In addition, the health benefits of enhanced ventilation are not well-understood by most tenants as of yet.

The environmental costs represent another potential barrier to adoption of higher ventilation rates. While these costs are real, especially when magnified by all buildings in the U.S., the per building environmental impact on greenhouse gas emissions is not as impactful as the estimated benefits. These environmental impacts can be offset at three levels: individual, building, and system level. Pursuing other design features that promote alternative transportation options for individuals can reduce the environmental impacts from the building overall (incentivizing biking, preferred parking for electric cars, public transportation access). On a building-level, similar to the energy cost analysis, when ERVs are used the overall effect can be a net reduction in greenhouse gas emissions for the building. The environmental impacts can be reduced further through the use of more energy efficient HVAC systems, and, in new buildings, incorporation of advanced air distribution systems that deliver ventilation when and where it is needed to raise the effective ventilation per person, as opposed to the current approach of whole-building ventilation [23]. Last, on a systems-level, in cities with a greater percentage of use of non-combustion energy sources there is a lower environmental cost associated with enhancing ventilation.

The energy and environmental impacts are offset by the dramatic positive impacts that enhanced ventilation has on human health and productivity. In our recent study of office workers, when we mapped raw test scores onto normative data we found an eight percentile increase in decision-making performance when ventilation was increased from 20 cfm/person to 40 cfm/person, corresponding to a $6500 change in a typical office worker's productivity. This is a conservative estimate of productivity gains and economic costs. First, the analysis in this paper only investigates cognitive impacts while in the office. The impacts of ventilation on other domains of health are well documented in the literature and lead to significant economic costs [24]. The risk of sick leave, illness, influenza and pneumonia are all elevated at lower ventilation rates and have additional productivity impacts (Table 2.5).

Table 2.5 Health impacts of ventilation rate in medium office prototype building (adapted from Fisk *et al.* [24]).

Reference	Outcome	Ventilation Rate (cfm/Person)		Relative Risk
		Low	High	
Milton *et al.* [25]	Short term sick leave	12.9	25.8	1.5
Brundage *et al.* [28]	Illness all years	4.5	30	1.5
Brundage *et al.* [28]	Illness 1983 data	4.5	30	1.9
Drinka *et al.* [29]	Illness	48	120	2.2
Drinka *et al.* [29]	Influenza	48	120	4.7
Knibbs *et al.* [30]	Influenza	15	45	3.1
Knibbs *et al.* [30]	Rhinovirus	15	45	2.1
Knibbs *et al.* [30]	TB	15	45	3.3
Hoge *et al.* [31]	Pneumonia	20.4	30	2.0
Stenberg *et al.* [32]	SBS symptoms	8.5	42.4	5.0

With respect to sick leave, the cost per occupant is estimated to be an extra $400 each year at reduced ventilation rates [25]. The same study found this impact alone to dwarf energy costs by a factor of six among corporate workers. Second, as outdoor CO_2 levels and temperatures rise as a result of climate change, the energy usage and IEQ of poor and high performing buildings will become increasingly disparate [26]. Third, our analysis only accounts for the direct costs associated with salaries; the employer cost for employee compensation is approximately 30% higher when considering benefits [22]. As higher paid positions have more expensive benefits, the reduction in costs to the company will be higher than estimated in this analysis. Fourth, the testing occurred in a LEED platinum building with low chemical concentrations. Even larger cognitive deficits were observed when chemicals were added to the space [15]. Enhanced ventilation in buildings with poor IAQ will lead to larger productivity gains than what was seen in this green environment. Lastly, the cognitive domains that have the highest correlations with other measures of productivity such as education level, salary at age, and number of employees supervised were the ones that had the largest improvements at higher ventilation rates [27]. The participants shifted from the 46.5th percentile to the 57th percentile on the information usage, strategy, and crisis response domains.

These findings indicate that standard HVAC design and operation are not optimal for occupant health and decision making. New building construction should include ERVs and systems that can provide modifiable ventilation rates depending on outdoor air conditions. They should also invest in other ventilation strategies such as advanced air distribution systems and improved filtration, which reduces contaminants that may cause cognitive impacts. Green building architects and designers, which have the goal of improving occupant wellbeing while simultaneously reducing their environmental impact, should be particularly cognizant of ventilation strategies that can optimize these two factors. Credit-based rating systems should revisit their design requirements and properly incentivize these approaches.

Many existing buildings, on the other hand, have HVAC systems that are designed for a specific ventilation rate and may not be easily modified to increase ventilation rates. This limits the ability of building managers to make changes to the ventilation rate, even in light of the evidence presented in this paper. This limitation is similar for ERVs, which may not be easily installed into some existing systems.

Our analysis focused on one office type—the Department of Energy "Medium Office Type" template—and may not be applicable to other building types. In addition, this research and our previous research on cognitive function did not explicitly investigate thermal conditions, which may have independent productivity impacts. However, the modeling is straightforward and building owners for all buildings types could replicate our analysis for their specific building to estimate indoor conditions, energy costs, and environmental impacts. Last, energy costs fluctuate, but in our analysis model inputs are based on local costs and energy fuel mix as of the date that this manuscript was submitted. Any changes to the fuel mix or costs will change our estimated costs. Regardless, variation in the overall energy costs per occupant will be minor relative to their employment costs.

Several assumptions were made to derive the economic benefits of improved ventilation. First, we assume that the population of knowledge workers that took the cognitive testing was representative of the U.S. office workforce. 20% of that group held management positions compared to 12% in the BLS data, and 60% had professional occupations compared to 50% in the BLS data. Second, we assume a one percentile change in cognitive function corresponds to a one percentile change in value as an employee (e.g., someone who scores in the 62nd percentile is salaried at the 62nd percentile). Previous work with the SMS tool has shown high correlations (>0.6) between cognitive scores and salary [27]. Third, this analysis demonstrates the competitive advantage to be gained by improving ventilation in comparison to workforce at large. As improvements to ventilation are adopted by a larger percentage of buildings, there will be an equilibration of wages to account for a generally more productive workforce.

2.5 Conclusions

The public health benefits of enhanced ventilation far exceed the per occupant economic costs in U.S. cities. Even with conservative estimates, the increased productivity of an employee is over 150 times greater than the resulting energy costs. Environmental costs are also relatively minor, but should be offset by the incorporation of energy recovery systems, advanced ventilation strategies, and other green building design strategies.

Author Contributions

Pegues is an engineer at United Technologies Building and Industrial Systems and conducted the initial energy analysis for this study. The remaining environmental and public health analyses and interpretation of the energy modeling were conducted by MacNaughton. Satish helped with the productivity analysis. The paper was written by MacNaughton and Allen. All authors reviewed the final manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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CHAPTER 3 - The Impact of Working in a Green Certified Building on Cognitive Function and Health

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Abstract

Thirty years of public health research have demonstrated that improved indoor environmental quality is associated with better health outcomes. Recent research has demonstrated an impact of the indoor environment on cognitive function. We recruited 109 participants from 10 high-performing buildings (i.e. buildings surpassing the ASHRAE Standard 62.1-2010 ventilation requirement and with low total volatile organic compound concentrations) in five U.S. cities. In each city, buildings were matched by week of assessment, tenant, type of worker and work functions. A key distinction between the matched buildings was whether they had achieved green certification. Workers were administered a cognitive function test of higher order decision-making performance twice during the same week while indoor environmental quality parameters were monitored. Workers in green certified buildings scored 26.4% higher on cognitive function tests than those in non-certified buildings, controlling for annual earnings, job category and level of schooling. Thermal comfort and the previous night's sleep quality were predictors of cognitive function scores. Sleep Scores were 6.4% higher for participants in green certified buildings, suggesting an impact of the building on sleep quality that evening. We describe a holistic "buildingomics" approach for examining the complexity of factors in a building that influence human health.

Keywords: Green Certification, Office Buildings, Cognitive Function, Indoor Environmental Quality, Buildingomics

3.1 Introduction

Thirty years of public health science and building science have demonstrated that buildings play a key role in shaping our health [1-5]. Buildings have the capacity to create conditions that are harmful to health or conducive to health: they determine our exposure to outdoor pollutants, by either facilitating entry of particles of outdoor origin indoors, or acting as a barrier and removing them through enhanced filtration [6]; they govern exposure to chemicals of concern, such as volatile organic compounds (VOCs), flame retardants and polyfluorinated compounds, which can be ubiquitous or nonexistent, depending on the decisions we make regarding building materials and products [7, 8]; buildings either protect us from noise or contribute to the problem through the introduction of indoor sources, poor noise insulation, or poor acoustical design [9, 10]; they can induce eye strain or improve alertness through impacts on circadian rhythm, depending on the lighting system [11, 12]; buildings can protect us during heat events, or create environments that magnify the problem through solar heat gain [13, 14]; and buildings can either wall us off from nature or connect us to it [15, 16].

The scientific literature around buildings and health has identified the foundations of a healthy building including factors such as ventilation, air quality, thermal comfort, noise and lighting, and this body of research has served as the basis for green certification standards to define their indoor environmental quality (IEQ) guidelines. A review of leading, global green-building standards - LEED New Construction 2009, Green Star Office v3, BREEAM New Construction 2012, BCA Green mark for new non-residential buildings v4.1 2013, and DGNB New Office v2012 - demonstrates the approach of these certification standards toward IEQ. All of the rating systems offer credits for thermal comfort, indoor air quality (IAQ) and lighting; all but LEED NC 2009 have credits for acoustics; and Green STAR v3 and LEED NC 2009 have credits specifically for ventilation. However, building owners and developers can opt for certain credits, and IEQ represents only 4-20% of the total score a building can obtain. Of the reviewed rating systems, only LEED NC 2009 has mandatory IEQ credits, for minimum IAQ performance and environmental tobacco smoke control [17].

The adoption rates of the optional IEQ credits in LEED NC 2009 give an indication of how building owners are prioritizing certain aspects of IEQ [17]. We extracted the data and found that the vast majority of projects obtain credits for low-emitting adhesives, paints and flooring systems (Table 3.1). Increased ventilation is much less widely adopted, despite strong evidence for health and performance benefits of higher ventilation rates [18, 19]. While some credits are preferentially adopted and others not, buildings that seek LEED NC 2009 obtain on average 9 of the 15 possible IEQ credits, not including the required fundamental commissioning credit under the energy and atmosphere credit category.

Table 3.1 Credit adoption rates for select optional IEQ credits in 5,490 LEED New Construction 2009 certified buildings (USGBC, 2016).

Credit	% Adoption
EQc2: Increased ventilation	40.9%
EQc4.1: Low-emitting materials - adhesives and sealants	86.5%
EQc4.2: Low-emitting materials - paints and coatings	94.4%
EQc4.3: Low-emitting materials - flooring systems	79.1%
EQc4.4: Low-emitting materials - composite wood and agrifiber products	58.6%
EQc5: Indoor chemical and pollutant source control	40.7%
EQc6.1: Controllability of systems – lighting	66.4%
EQc6.2: Controllability of systems - thermal comfort	39.1%
EQc7.1: Thermal comfort – design	79.4%
EQc7.2: Thermal comfort – verification	59.2%
EQc8.1: Daylight and views – daylight	19.5%
EQc8.2: Daylight and views – views	38.3%

The literature suggests that these credits translate into improved IEQ. Our previous review of green buildings and health identified 17 studies and found that, overall, occupants report better IEQ and fewer health problems in these buildings compared to non-certified buildings. These studies found lower levels of VOCs, formaldehyde, allergens, nitrogen dioxide, and particulate matter in green buildings, which have been separately shown to impact health. Six of the reviewed studies tracked the health of occupants in addition to IEQ, and all six found improvements in the green buildings [20]. These include reduced asthma and allergy symptoms in offices [21]; reduced respiratory symptoms, fewer sick building symptoms, and better self-reported well-being in public housing [22-24]; and fewer medical errors and decreased mortality in hospitals [25]. Of these studies, Newsham et al. used an approach similar to this study by recruiting green and conventional office building pairs and measuring IEQ. They found an improvement in IEQ, a reduction in symptoms, and better reported sleep quality in the green buildings [26]. A follow up paper by Colton et al. published since the time of our review found that in addition to fewer asthma symptoms, hospital visits and school absences were reduced in the green certified public housing development [27]. Comparisons of buildings in poor condition to green buildings provide an opportunity to see the biggest potential effect, but may falsely attribute benefits to certification.

As part of our efforts to determine the factors that drive better human health in buildings, we previously conducted a study in a controlled setting to investigate several IEQ factors – ventilation, CO_2, and VOCs – and their impact on cognitive function scores. We found significant impacts on human decision-making performance related to all three of these factors (Allen et al., 2015). Others have also found independent effects of ventilation, CO_2 and VOCs on cognitive function and other physiological responses at levels commonly found in indoor environments [19, 28-31]. In this current study, we looked at buildings that are high-performing across these indicators of IEQ and investigated the potential for additional benefits of green certification on cognitive function, environmental perceptions, and health.

3.2 Methods

3.2.1 Study Design - Overview

Workers from 10 office buildings in five U.S. cities (two buildings per city) were recruited to participate in a week-long assessment. 12 participants were initially recruited from each building. Participants completed surveys about their health and environmental perceptions and took a cognitive test on the Tuesday and Thursday of the assessment. All buildings were high-performing buildings, defined as buildings surpassing the ASHRAE Standard 62.1-2010 minimum acceptable per person ventilation requirement and with low (<250 $\mu g/m^3$) TVOC concentrations; however, six of the buildings were green certified via the LEED certification framework while the remaining four were not [32].

3.2.2 Participant and Building Recruitment

The building assessments took place in urban areas of the following cities: Boston, Massachusetts (9/29/2015-10/2/2015); Washington DC (10/26/2015-10/30/2015); Denver, Colorado (11/9/2015-11/13/2015); San Jose, California (11/30/2015-12/4/2015); and Los Angeles, California (12/14/2015-12/18/2015 and 2/1/2016-2/5/2016). In each city, the buildings were matched strictly by tenant and loosely by age and size (Table 3.3). In the first four cities, the buildings were also matched by the dates of assessment, and the buildings were recruited such that one building was LEED-certified and the other not. The goal of matching was to select two high-performing buildings in each city that were as similar to each other as possible with the key distinction being that one pursued LEED certification. In the last city, Los Angeles, two green certified buildings were recruited and the assessments occurred on different dates due to an earlier enrolled building dropping out of the study prior to the assessment; a second building was subsequently recruited. The study team visited each building prior to the assessment to: 1) perform a an initial assessment of the heating, ventilation and air conditioning (HVAC) systems, 2) ensure that the building classification as high-performing was valid, and 3) recruit participants.

After obtaining permission from the building owner, building management and tenant, 12 participants were recruited to participate in a five day health assessment in each building. Final participant numbers by building are presented in Table 3.3. As mentioned previously, the same tenant was used in each city to ensure similar work functions, and all of the companies employ primarily knowledge workers (i.e. administrative, professional, technical and managerial positions). Asthmatics were excluded during recruitment. We did not restrict recruitment to select areas of each building to limit potential selection bias. The study protocol was reviewed and approved by the Harvard T.H. Chan School of Public Health Institutional Review Board. All participants signed informed consent documents and were compensated $100.

Table 3.2 Demographic breakdown of participants in each building classification.

	High-Performing Green Certified	High-Performing Non-Certified
Number of Participants[1]	69	40
Gender		
Male	55%	54%
Female	45%	46%
Age		
20-30	39%	28%
31-40	21%	33%
41-50	21%	15%
51-60	18%	15%
61-70	1%	8%
Ethnicity		
White/Caucasian	70%	56%
Black or African American	6%	10%
Asian	7%	8%
Latino	7%	13%
Other	9%	13%
Highest level of Schooling		
High School Graduate	0%	10%
Some College	12%	26%
College Degree	63%	49%
Graduate Degree	25%	15%
Job Category		
Managerial	22%	10%
Professional	45%	54%
Technical	6%	18%
Secretarial or Clerical	18%	15%
Other	9%	3%
Total Annual Earnings		
<$50,000	34%	13%
$50,000-$75,000	21%	41%
$75,000-$100,000	10%	21%
$100,000-$150,000	27%	18%
>$150,000	7%	8%

[1] Includes 2 participants in green certified buildings and 1 in non-certified buildings who did not complete the baseline survey

3.2.3 Building Assessment

The building assessment consisted of three parts. First, the study team conducted an inspection of the building systems along with the building engineers from each facility. The study team recorded the type and condition of the systems, how they are typically operated, and the frequency of building commissioning tasks such as changing the filters. Second, the study team characterized each test space. The test spaces were defined by the unique ventilation zones in which the participants were located. The baseline assessment of the test spaces characterized the building, office and cleaning materials in the space; the air supply and exhaust strategies; and the environmental controls such as operable windows and thermostat set points. On each cognitive testing day, a separate assessment was conducted of the ventilation rates, noises, odors and occupancy in each test space. Lastly, the building manager was provided a survey asking about general building information, building policies, and utility costs. All elements of the building assessment were adapted from the EPA BASE study [33]. These elements were designed to assess the building as a whole rather than just the IEQ of the participant's workstations.

Table 3.3 Building characteristics of the 10 high-performing buildings included in the study.

City	Type	Size (sq. ft)	Year of Construction	Type/Year of Certification[1]	Ventilation Strategy[2]	Number of Participants
Boston	Non-Certified	<50,000	1929	NA	CV, RC	12
Boston	Certified	<50,000	1929	LEED EB v3 Platinum in 2012	VAV, SP	12
DC	Non-Certified	>500,000	1935	NA	VAV, RC	11
DC	Certified	>500,000	1917	LEED EB v3 Gold in 2010	CV, SP	12
Denver	Non-Certified	50,000-100,000	1938	NA	CV, RC	8
Denver	Certified	50,000-100,000	1938	LEED CI v3 Silver in 2011	CV, RC	12
San Jose	Non-Certified	50,000-100,000	1971	NA	CV, RC	9
San Jose	Certified	>500,000	1934	LEED EB v3 Gold in 2015	VAV, RC	12
Los Angeles	Certified	<50,000	1953	LEED EB v3 Platinum in 2013	VAV, RC	11
Los Angeles	Certified	<50,000	1929	LEED EB v4 Platinum in 2016	VAV, RC	10

[1] EB = Existing Buildings, CI = Commercial Interiors

[2] CV = Constant Volume, VAV = Variable Air Volume, SP = Single pass with energy recovery ventilator, RC = Partial recirculation with reheat

3.2.4 Environmental Assessment

A complete characterization of the IEQ in each test space was conducted on each cognitive testing day. Each participant was outfitted with a Netatmo Weather Station (Netatmo, Boulogne-Bellancourt) in their cubicle to measure temperature, humidity, carbon dioxide concentrations in parts per million (ppm), and sound levels (in decibels) every 5 minutes for each participant. The units were tested with 400 and 1000 ppm CO_2 calibration gas before and after the field campaign. If the sensor had drifted, the CO_2 data was adjusted first by the offset from the 400 ppm reading and second by a scaling factor to match the 1000 ppm reading of the instrument to 1000 ppm. This process corrected both the intercept and slope of the collected data to match experimentally derived values. The CO_2 data was then used to produce ventilation (cfm of outdoor air per person) and air exchange rates (ACH) for each participant-day of the study. For ventilation rate, the 90^{th} percentile CO_2 concentration during occupied hours was taken as the steady-state concentration of CO_2 using the method described by Ludwig et al., and for air exchange rate, the decays curves of CO_2 were analyzed using the tracer gas method described in ASTM Standard E741-11 [34, 35]. Briefly, when test spaces changed from fully occupied to unoccupied, the rate of decay of occupant generated CO_2 can be used to estimate air exchange rates using the validated methodology set forth by ASTM.

Air sampling was performed for 62 common VOCs and 14 common aldehydes in each building in the test space with the most participants present during each cognitive testing day. VOCs were collected using summa canisters according to EPA method TO-15. Aldehydes were collected on an 8-hour integrated active air sample (0.4 L/min flow rate) according to EPA method TO-11. ALS Analytical Laboratories conducted the analyses of these samples (Cincinnati, OH). 25 VOCs and four aldehydes were not detected in any of the samples. Each test space was also equipped with at least one commercial sensor package (FengSensor, Tsinghua University, Beijing) to measure the same parameters as the Netatmo as well as light levels in lux and particulate matter less than 2.5 µm in diameter ($PM_{2.5}$) in $\mu g/m^3$. These sensors were installed on the first day of the assessment (Monday) and collected on the final day of the assessment (Friday).

3.2.5 Health Assessment

Participants were provided a Basis Peak Watch (Basis an Intel Company, San Francisco) for the duration of the assessment, which tracked the participants' heart rate, skin temperature, galvanic skin response, physical activity (i.e. steps and calorie expenditure) and sleep patterns (i.e. sleep duration, tossing and turning, number of interruptions). The participants also completed a series of questionnaires over the course of the study. The first was a baseline survey about their perceptions of their work environment and health. The second survey was completed each study day at the end of the workday, a total of five times for each participant, which asked about their environment and whether they experienced any of 19 sick building syndrome (SBS) symptoms on that day. A follow-up survey was completed on the final day of the study asking questions about the previous week, such as satisfaction with noise, lighting, thermal comfort and odors in their cubicle. These surveys were adapted from the EPA BASE study as well and used in our previous research on green buildings [30, 33].

Cognitive function was assessed using the Strategic Management Simulation (SMS) software on Tuesday and Thursday at approximately 15:00. The participants completed two different scenarios to avoid potential learning effects, and the frequency of each scenario was balanced between green certified and non-certified buildings. The SMS tool is a validated, computer-based test that measures higher-order decision making ability across nine domains of cognitive function, ranging from basic activity levels to strategy. The SMS tool has been extensively described in the literature [36-38]. Briefly, the SMS tool immerses the participant in a 1.5 hour long real-life scenario, where they have to respond to several plot lines that emerge over the course of the simulation. These plot lines are validated for content and designed to capture cognitive functions representative of productivity in the real world. They are given the flexibility to approach the simulation in their own thinking style, with no stated demands and a wide breadth of available responses. The types of decisions and plans the participant makes and the events to which they link these actions are processed by the software through a series of algorithms that compute scores for each domain. The SMS study team is blinded to the building status (green certified vs. non-certified). Participants' cognitive function scores on Tuesday and Thursday were, on average, highly consistent. More detailed methodology about the cognitive testing is described elsewhere [19, 29, 39].

3.2.6 Statistical Methods

The IEQ data collected in this study experienced building-level clustering, which was accounted for with hierarchical statistical tests. Two-sample t-tests with clustered data were used to test for significant differences in IEQ between green certified and non-certified buildings. For analyses of participant outcomes, such as cognitive function and sleep, the data was additionally clustered by the repeated measurements on each participant. Generalized linear mixed effect models were used to model the associations between building classification and these outcomes, treating participant ID and building ID as a random effect:

$$Cog.Score_{i,j,k} = \beta_1 + \beta_2 * (Green\ Certified) + b_{1i} + b_{2i,k} + e_{i,j,k} \qquad (1)$$

where $Cog.Score_{i,i,k}$ is the average cognitive score for subject i on day j in building k, normalized to the non-certified, high-performing buildings; β_1 is the fixed intercept; β_2 is the fixed effect of high-performing, certified buildings compared to high-performing, non-certified buildings; b_{1i} is the random effect of intercept for subject i; and $b_{2i,k}$ is the random effect of intercept for building k. Additional models were run with the following variables: job category, annual earnings, level of schooling and thermal comfort as indicator variables and previous night's sleep as a continuous variable. The residuals were normally distributed and homoscedastic for all models. We used penalized splines to graphically assess linearity in the associations between continuous variables and outcome measures.

The SMS tool provides raw scores for nine domains of cognitive function. To allow comparisons between domains, the cognitive function scores were normalized to scores in the non-certified building by dividing each score by the average score in the non-certified buildings in that domain, as has been done in previous studies using the SMS test [39]. The average cognitive score is an average score across the nine domains. Thermal comfort is a binary variable that reflects whether or not a participant was within the thermal comfort zone specified by ASHRAE Standard 55-2004 on any particular day of the assessment [40] (Figure 3.1). Relative humidity and temperature from the Netatmo were entered in the Fanger thermal comfort equations to estimate whether the percent of people dissatisfied with the thermal conditions would exceed 10% [41]. We assume constant radiant temperatures (same as dry bulb temperature), air velocities (0.15 m/s), metabolic rates (1 met), and clothing (1 clo) between participants.

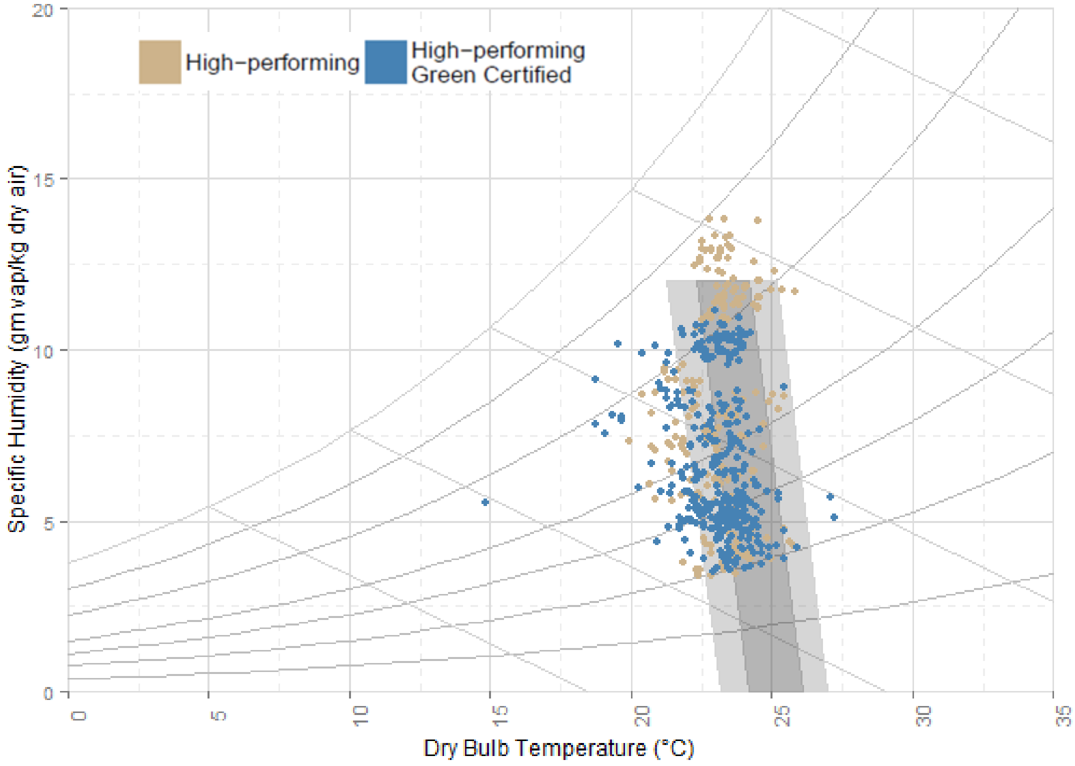

Figure 3.1 Thermal comfort for each participant-day by building type plotted on the psychrometric chart. The light gray region corresponds to a Percent of People Dissatisfied (PPD) below 10%, and the dark gray region corresponds to a PPD below 7% as derived from ASHRAE Standard 55-2010 (ASHRAE, 2010).

To assess sleep, we developed an index to characterize each night of sleep across three well-known indicators of sleep quality: sleep duration, tossing and turning, and number of interruptions. It was calculated using data from the Basis Watch for each night of sleep the participants had during the assessment according to equation (2):

$$Sleep\ Score = 100\% \cdot \frac{Sleep.Duration}{420} - 10\% \cdot \frac{Toss.Turn}{85} - 10\% \cdot \frac{Num.Int}{4} \qquad (2)$$

where Sleep.Duration is the number of minutes the participant spent sleeping between 9PM and 9AM the following day, Toss.Turn is the number of minutes during which the watch registered motion via the accelerometer (the maximum Toss.Turn in this study was 85), and Num.Int is the number of times during a night of sleep that the sleep activity changed from asleep to awake and then back to asleep (the maximum Num.Int in this study was 4). If the participant slept for longer than 420 minutes, or 7 hours, the first term was capped at 100%. Nights when the watch was not worn or worn improperly were removed from the analysis, resulting in a total sample size of 260 nights, 100 of which preceded a cognitive testing day. The average Sleep Score was 83.1% with a standard deviation of 19.7%. Analyses were performed using the open-source statistical package R version 3.2.0 (R Project for Statistical Computing, Vienna, Austria).

3.3 Results

The non-certified buildings and green certified buildings had similar air quality; the low CO_2, low TVOC and high ventilation rates indicate that the buildings were high-performing at the time of the assessment (Figure 3.2). The ventilation rates exceeded the ASHRAE 62.1-2010 standard for 84% of participants, which could mitigate the buildup of airborne contaminants. The green certified buildings were on average brighter (374 lux vs. 163 lux), louder (51.8 dB vs. 48.9 dB), and drier (38.4% vs. 45.9%) than the non-certified buildings; however, only the difference in relative humidity was statistically significant (Figure 3.2). Differences in humidity may be driven by the ventilation strategies in the green certified buildings, which more frequently had variable air volume ventilation systems.

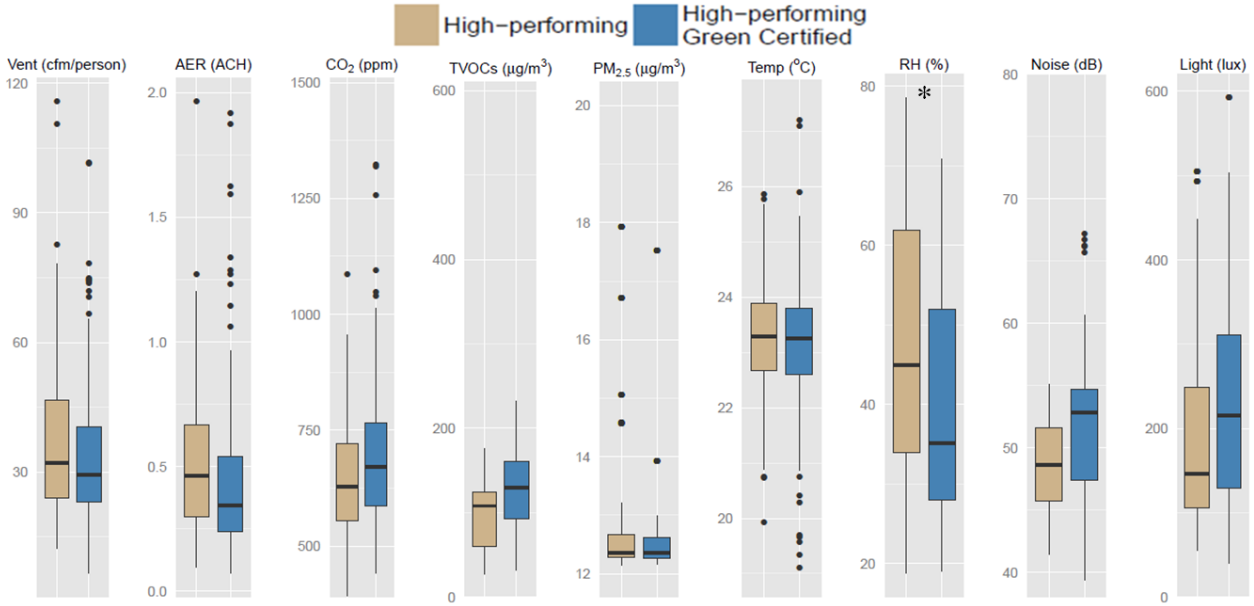

Figure 3.2 Boxplots of indoor environmental quality (IEQ) parameters in high-performing, non-certified buildings and high-performing, green certified buildings. Vent, AER, CO_2, Temp, RH and Noise are measured by the Netatmo in every workstation each day, TVOCs are measured with summa canisters in every test space each cognitive testing day, and $PM_{2.5}$ and Light are measured by the Feng Sensor in every test space each day. An asterisk (*) denotes that the building classifications are statistically significantly different from each other for that IEQ parameter after adjusting for clustering by building.

Between-subject analyses were necessary to compare participants in different building classifications. Table 3.2 shows the demographic information for the participants in each building classification: the matching criteria resulted in the two groups having similar job classifications, gender and ages. The green certified buildings had a slightly larger percentage of white/Caucasian participants and participants with a college or graduate degree. These buildings also had more participants at both the lower and higher end of the range of annual earnings. We added these variables as predictors to the cognitive function models to test if they influenced baseline cognitive abilities, and none of these predictors were statistically significantly associated with cognitive function scores or influenced the effect estimate of building classification.

The impact of building classification on each domain of cognitive function is summarized in Figure 3.3. On average, participants in the high-performing, green certified buildings scored 26.4% higher on the SMS cognitive test than those in the high-performing, non-certified buildings (p-value < 0.001). Cognitive scores were statistically significantly higher for 7 of the 9 domains with the largest impacts on crisis response, applied and focused activity level and strategy. No differences in scores were seen for basic activity level or information seeking. For the average scores, the model's R^2 was 0.28, indicating that 28% of the variability in cognitive function scores is explained by the building classification alone.

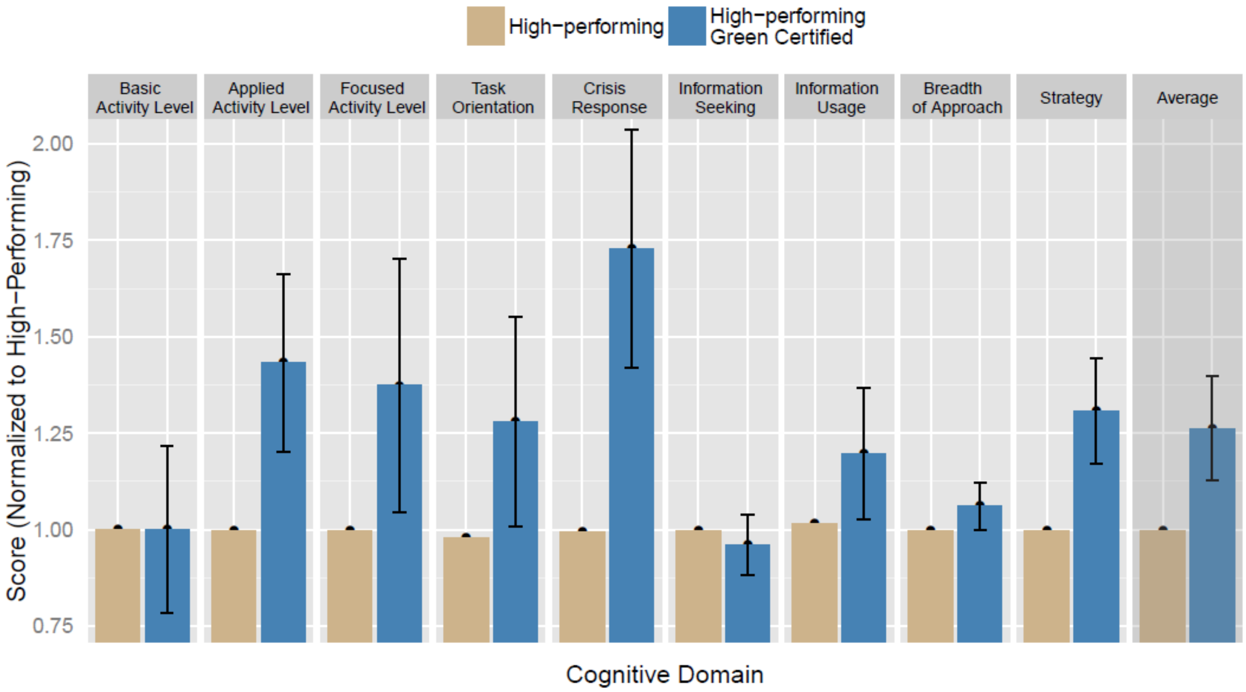

Figure 3.3 Cognitive scores and 95% confidence intervals for each domain of the SMS tool after controlling for participant, normalized to high-performing buildings, for participants in high-performing and high-performing, green certified buildings.

Of the IEQ parameters assessed in the buildings, the largest differences were seen for relative humidity. The non-certified buildings were more frequently outside the ASHRAE Standard 55 thermal comfort zone than the green certified buildings due to their higher humidities (Figure 3.1). Both building classifications had participant-days where the building was too cold to comply with ASHRAE Standard 55. After controlling for building classification, participants within the thermal comfort zone scored 5.4% higher on the SMS cognitive tests than those without (Figure 3.4).

Previous night's sleep was also associated with cognitive function scores. A 25% increase in Sleep Scores was associated with a 2.8% increase in cognitive function scores. Sleep quality was influenced by day-time exposures in the office: participants in the green certified buildings had 6.4% higher Sleep Scores than those in the non-certified buildings. This may be in part a result of higher light levels in the green buildings; a 300 lux increase in illuminance during the day was associated with a 2.9% increase in Sleep Scores that night. However, these findings are not statistically significant (Figure 3.4).

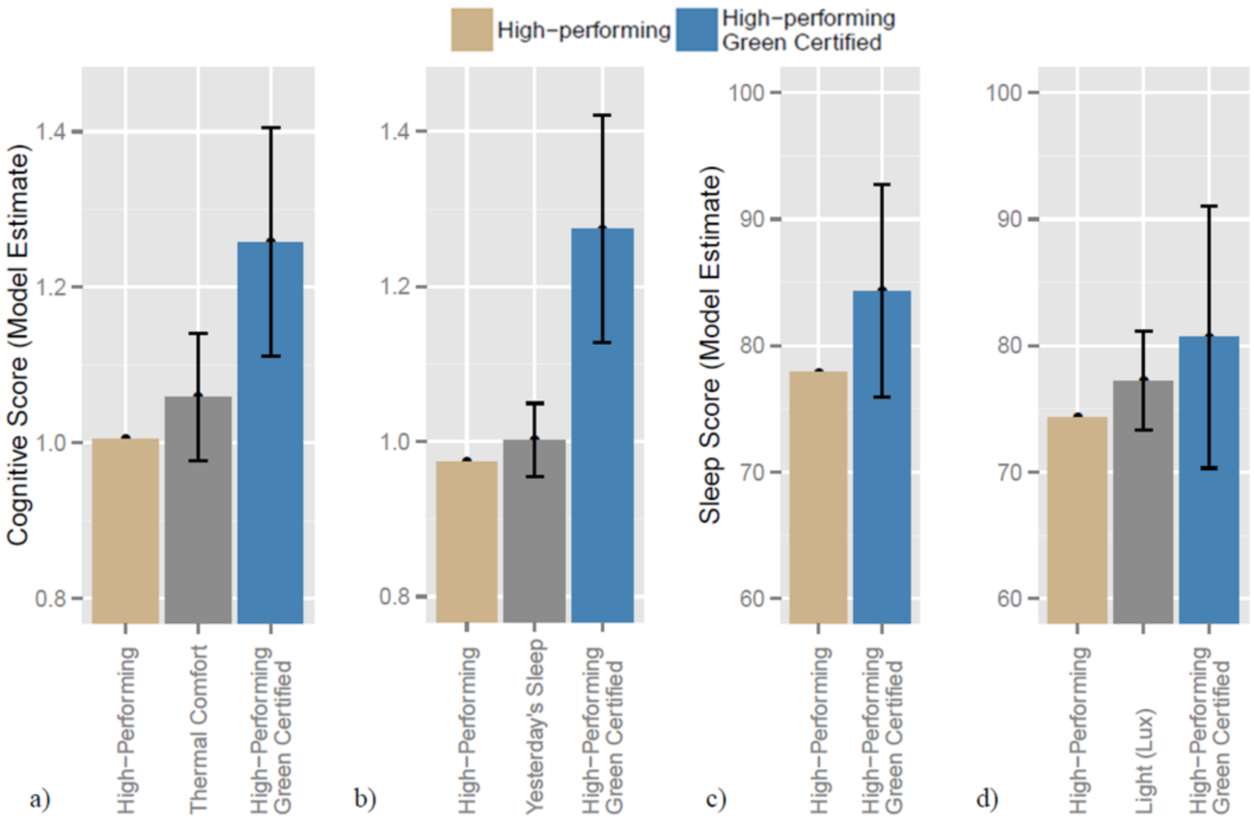

Figure 3.4 Effect of **a)** thermal comfort on cognitive function scores, **b)** yesterday's sleep on cognitive function scores, **c)** building classification on Sleep Scores, and **d)** light levels on Sleep Scores, using generalized linear mixed effect models with 95% confidence intervals, treating building and participant as random effects. The effect size for thermal comfort is comparing cognitive scores from tests taken by participants within the ASHRAE Standard 55-2013 comfort zone to those without. The effect sizes for yesterday's sleep and light correspond to a 25% change in Sleep Score and 300 lux change in illuminance respectively.

In addition to improved cognitive function scores, participants in green certified buildings reported better environmental perceptions and fewer symptoms than those in non-certified buildings. Participants in green certified buildings were generally more satisfied with daylighting and electrical lighting in their workspace, and less frequently reported the temperature being too hot or too cold, the air movement being too much or too little, the air being too dry or too humid, and the presence of chemical, tobacco and other odors (Figure 3.5). These perceptions are linked to the monitored IEQ in the spaces. For example, relative humidities were 15.9% higher when participants reported the air was too humid. Lastly, participants in the non-certified buildings reported 0.5 (30%) more symptoms each day than those in the green certified buildings.

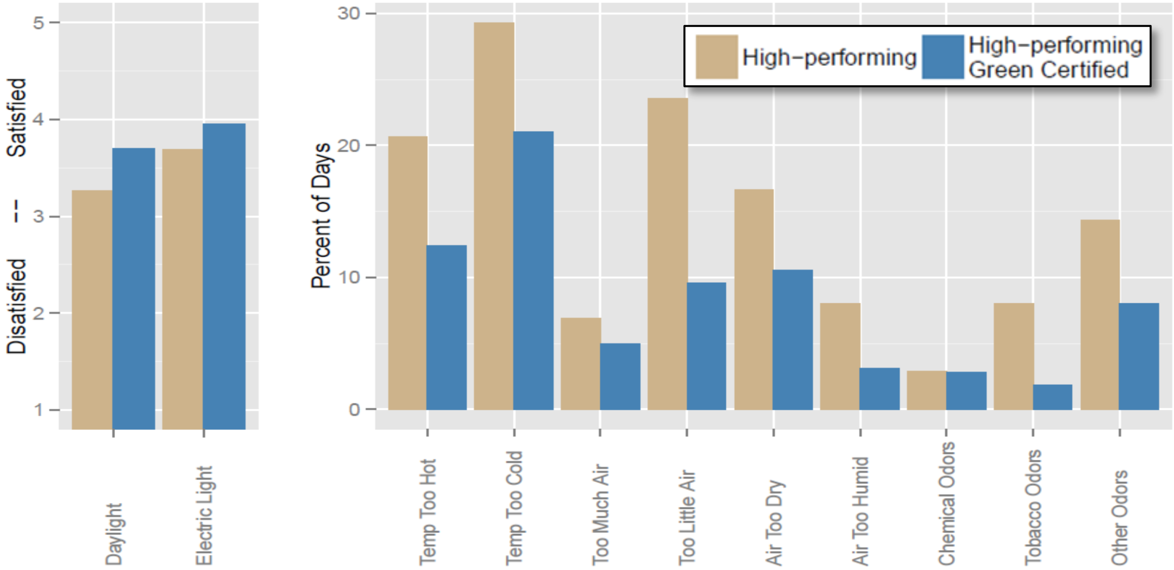

Figure 3.5 Environmental perceptions of lighting, temperature, air movement, humidity and odors in high-performing, green certified and high-performing, non-certified buildings. Participants were asked about lighting conditions at the end of the assessment on a Likert scale ranging from Very Dissatisfied (1) to Very Satisfied (5), and asked about the presence of temperature, air movement, humidity and odor problems daily.

3.4 Discussion

Previous research by our team, and others, has identified IAQ as a key driver of cognitive function. In particular, CO_2, TVOCs, and ventilation all have independent impacts on cognitive function, even at levels deemed to be acceptable by the relevant codes and standards [19, 28, 29, 39]. Many office buildings on the market now fit the classification as high-performing by surpassing the ASHRAE Standard 62.1 ventilation requirement and having low TVOC concentrations (<250 $\mu g/m^3$). The findings of this study indicate that even among high-performing buildings that meet these IEQ criteria, additional benefits to cognitive function and health may be achieved by seeking green building certification. Participants in high-performing, green certified buildings had 26.4% higher cognitive function scores and 6.4% higher Sleep

Scores than participants in the high-performing, non-certified buildings even after controlling for annual earnings, job categories, and level of schooling.

While most IEQ parameters were similar between the two types of buildings, thermal comfort indicators differed and were a significant determinant of cognitive function. The green certified buildings were generally less humid than the non-certified buildings, and as a result a larger proportion of participants in these buildings were in the thermal comfort zone defined by ASHRAE 55 (Figure 3.1). Participants outside this thermal comfort zone scored 5.4% lower on the cognitive simulations. The detriments to cognitive function align with previous research on thermal conditions and performance. In a review of 24 papers, Seppänen et al. found that work performance was optimized at temperatures within the ASHRAE Standard 55 zone, and that the benefits were seen using various different indicators of cognitive function ranging from simple cognitive tests to objectively reported work performance [42]. The impacts on the SMS tool indicate that high order decision-making is also affected by these exposures.

Not surprisingly, our study identified the previous night's sleep as a driver of cognitive function. More interesting is that better sleep quality was associated with better lighting conditions in the building. This is biologically plausible, considering previous research linking exposure to daylighting or blue-enriched lighting before sleep to sleep repression. Warmer light colors, such as those at dusk, trigger the body to release melatonin, which has a fatiguing effect, and late-night screen use can delay or suppress the release of melatonin [43]. Similarly, a larger contrast between daytime light exposures and nighttime light exposures leads to a larger amplitude in daily melatonin secretion cycles [44]. Daylighting and blue-enriched lighting during the day helps align the body's circadian rhythm and improve sleep quality at night [12]. This effect was observed in our study: brighter lighting in the office during the day was associated with higher Sleep Scores at night, and participants in the green certified buildings, which were generally brighter, had 6.4% higher Sleep Scores than those in the non-certified buildings. This finding supports previous research by Newsham et al. on sleep quality in green buildings [26].

Investigating real-world office buildings, as opposed to a simulated environment, posed several limitations on the study. First, the case-control study design required between-subject comparisons. To minimize baseline differences in cognitive function, we matched the buildings by tenant and job categories. Adding annual earnings, level of education, and job category to our models did not influence the effect size of building classification on cognitive function scores, nor were these factors statistically significantly associated with cognitive scores. Second, the environmental conditions were variable between buildings and could not be modified by the study team. The variability in exposures also limits the ability for the factors we did measure to produce a quantifiable effect. Third, missing data for some outcomes, such as sleep, reduced the power of those analyses. Fourth, while the sample size of participants was sufficiently powered, factors that vary on building level, such as ventilation system type, have a sample size of 10 and were underpowered. With this sample size we were not able to identify which individual green credits were drivers of better performance, nor were we able to obtain the same level of building-related design data from the non-certified buildings (precisely because they did not go through the certification process). As such, it is possible that green certification in our study may simply be a proxy for more relevant indicators of building performance. Fifth, we assessed the IEQ of the workstations of our participants, which may not be representative of the building as a whole. During our building assessment, we did not observe major differences in building systems, operation or maintenance for areas of the building in which we did not have participants. As the buildings were all high-performing, the results of the study may not be representative of conventional or problem buildings. In addition, the study population is representative of the general population of knowledge workers and may not be generalizable to other worker populations.

The findings in this study hint at the complexity of understanding all of the building related factors that can influence human health and performance. The measured IEQ variables only accounted for part of the impact of green certification on productivity and health. Other aspects of the green certification process – such as commissioning of building systems, 3rd party reviews of IEQ performance, and the commitment to sustainability and health of owners and building managers – may play a role in how occupants perceive and perform in a building. Here, we advocate for a holistic, "buildingomics" approach. Omics research describes efforts to understand the totality of a given research field, currently best exemplified by genomics research and the ambitious undertaking of the Human Genome Project. This has spurred a set of related – omics research areas: transcriptomics, proteomics, metabolomics, epigenomics. And, in the field of exposure science, the relatively new and equally challenging efforts to characterize human exposures over the course of a person's lifetime – the exposome [45]. We now propose "buildingomics" to capture the complexity of the research of health in buildings. "Buildingomics" is the totality of factors in indoor environments that influence human health, well-being and productivity of people who work in those spaces. The primary challenge is that buildings serve a variety of purposes and the potential exposures span several fields of study; thus multi-disciplinary teams that include building scientists, exposure scientists, epidemiologists, toxicologists, materials scientists, architects, designers, and social/behavioral scientists are necessary to characterize all the building-related factors that influence health in buildings.

3.5 Conclusions

Our findings show that in high-performing buildings additional benefits to health and productivity may be obtained through green certification. In a sample of 10 high-performing buildings, participants in green certified buildings had 26.4% higher cognitive function scores, better environmental perceptions and fewer symptoms than those in high-performing, non-certified buildings. The benefits of working in a green certified building extended beyond working hours: participants in green certified buildings had 6.4% higher Sleep Scores than those in non-certified ones. These outcomes were partially explained by IEQ factors, including thermal conditions and lighting, but the findings suggest that the benefits of green certification standards go beyond measureable IEQ factors. We describe the need for a holistic, "buildingomics" approach to studying the drivers of human health and performance in buildings.

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SUMMARY

The findings of this dissertation are clear: green buildings outperform non-certified or conventional buildings in terms of occupant cognitive function and health. In a controlled laboratory environment, several key environmental parameters were isolated and shown to impact cognitive function. Participants scored 61% higher on cognitive function tests when VOCs were reduced from over 500 $\mu g/m^3$ to less than 100 $\mu g/m^3$. Increasing outdoor air ventilation rates in the low VOC environment from 20 cfm/person to 40 cfm/person led to an additional 25% improvement in cognitive function scores. A significant portion of the benefit of increased ventilation is attributable to lower CO_2 levels. Independent of ventilation, CO_2 was shown to impact cognitive function scores. While holding outdoor air ventilation at 40 cfm/person, CO_2 was added to the environment to reach a steady-state CO_2 concentration consistent with the 20 cfm/person scenario. Participants scored 20% higher on cognitive tests at the low CO_2 concentration than at the higher CO_2 concentration. CO_2, as a proxy for ventilation, was also shown to impact heart rate and self-reported symptoms in a subsequent publication from this study. On average, participants had 43% more symptoms (p-value = 0.019) and a 2 bpm higher heart rate (p-value < 0.001) for a 1000 ppm increase in indoor CO_2 concentration (MacNaughton et al., 2016).

The benefits of green buildings are not fully encapsulated in these IEQ factors. Indeed, the mandatory credit on ventilation in LEED 2009 specifies the ASHRAE minimally acceptable ventilation rate, and credits for higher ventilation rates and low emitting materials are optional and adopted by 40.9% and 58.6%-94.4% of new building respectively. However, the benefits of green certification extend beyond these factors. In a sample of 10 buildings with high ventilation rates and low VOC concentrations, participants in green certified ones scored 26.4% higher on cognitive tests and had 6.4% higher Sleep Quality scores. The difference in performance is partly attributed to thermal comfort and better lighting, but much of the effect is unexplained. This is the basis for Buildingomics, which advocates for an exhaustive evaluation of the indoor environment in order to identify all the factors that influence performance and health. These types of evaluations will be necessary to understand the complex relationships between built environments and occupants.

Given the evidence shown in this dissertation and in the past 30 years of public health literature on buildings and health, it is evident that green buildings should be adopted preferentially over non-certified buildings. However, practitioners may cite economic and environmental barriers to designing and operating green buildings. A group of 1,423 developers, building owners, and tenants estimated the cost of constructing a green building to be 17% higher than a conventional building (WBCSD, 2007). In actuality, the cost margins of green construction are approximately 2%, according to an assessment of 33 green buildings. On the other hand, green buildings are, on average, 25-30% more energy efficient than conventional buildings, leading to a short return on cost margins and downstream environmental benefits (Kats et al., 2003). Importantly, in the operation phase of green buildings, energy efficiency can be obtained without compromising the indoor environment. In chapter 2 of this dissertation, we found energy use on ventilation to be essentially the same when 40 cfm of outdoor air per person is supplied with an ERV compared to when 20 cfm of outdoor air per person is supplied without an ERV. This change in ventilation rate correlates with a $6,500 productivity gain per occupant per year. By design, green buildings are better for the environment and occupant health. During operation, they can provide healthy indoor environments while simultaneously being more energy efficient than conventional buildings. The savings on energy and benefits to productivity can overcome the small marginal investment in opting for green certification.

In the past, the public health literature has served to steer practitioners, retroactively, away from building practices that lead to adverse health. For the first time in history, the academic literature on building design and operation is generally supportive of current commercial building practices. With this confluence of stakeholders, the opportunity to push the healthy building agenda is upon us. The buildings of today will be the buildings of the next 50 years or longer, so academics and practitioners alike must leverage the existing evidence on buildings and health to define the next generation of healthy buildings.

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