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# 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% (95% CI: [12.8%, 39.7%]) higher on cognitive function tests, controlling for annual earnings, job category and level of schooling, and had 30% fewer sick building symptoms than those in non-certified buildings. These outcomes may be 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 a holistic "buildingomics" approach for examining the complexity of factors in a building that influence human health.



## 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;

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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 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.

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.

## 2. Methods

### 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 are high-performing buildings, defined as buildings surpassing the ASHRAE Standard 62.1–2010 minimum acceptable per person ventilation requirement and with low (<250 μg/m3) TVOC concentrations; however, six of the buildings were renovated to green via the LEED certification framework while the remaining four did not seek green certification during renovation [32].

### 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). 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

**Table 1**
Credit adoption rates for select optional IEQ credits in 5490 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% |

participant numbers by building are presented in Table 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, but we are unable to demonstrate that our participants are representative of the building population. 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.

### 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. The building assessments did not intend to validate the certification of building; therefore, we cannot say whether the green certified buildings still meet the criteria for certification nor whether the non-certified buildings would classify as a green certified building had they gone through the certification process at the time of the study. We anticipate that the organizations responsible for the non-certified buildings would seek certification if it was possible since the same organizations did obtain certification for the green certified buildings in our study.

### 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 min 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. These approaches have some limitations; for example, air from other zones with elevated $CO_2$ levels can bias air exchange rate calculations and assumptions about occupant $CO_2$ generation rates may be inaccurate.

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-h 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 μg/m$^3$. These sensors were installed on the first day of the assessment (Monday) and collected on the final day of the assessment (Friday).

### 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, and how to interpret scores in each cognitive domain, has been extensively described in the literature [36–38]. Briefly, the SMS tool immerses the participant in a 1.5 h 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. As a result, validations of the SMS testing have found a high degree of correlation between performance on the SMS test and other indicators of productivity such as salary at age and number of employees supervised at age [36]. Participants 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].

### 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:

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

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; $\beta_1$ is the fixed intercept; $\beta_2$ 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] (Fig. S1). 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.

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):

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

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 min, or 7 h, 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%. Sleep Scores and thermal comfort were added to the model in Equation (1) to test their effect on cognitive function. Analyses were performed using the open-source statistical package R version 3.2.0 (R Project for Statistical Computing, Vienna, Austria).

## 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 (Fig. 1). 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 (Fig. 1). Differences in humidity may be driven by the ventilation strategies in the green certified buildings, which more frequently had variable air volume ventilation systems and energy recovery ventilators (ERVs). In the cases when outdoor humidity was high, buildings with ERVs had lower indoor humidity levels.

Between-subject analyses were necessary to compare participants in different building classifications. Table 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. While some of these variables had non-significant associations with cognitive test scores, the effect estimate of building classification did not change when these parameters were added to the model, indicating that the findings are not a result of residual confounding.

The impact of building classification on each domain of cognitive function is summarized in Fig. 2. On average, participants in the high-performing, green certified buildings scored 26.4% (95% CI: [12.8%, 39.7%]) 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.

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 (Fig. S1). Both building classifications had participant-days where the building was too cold to comply with

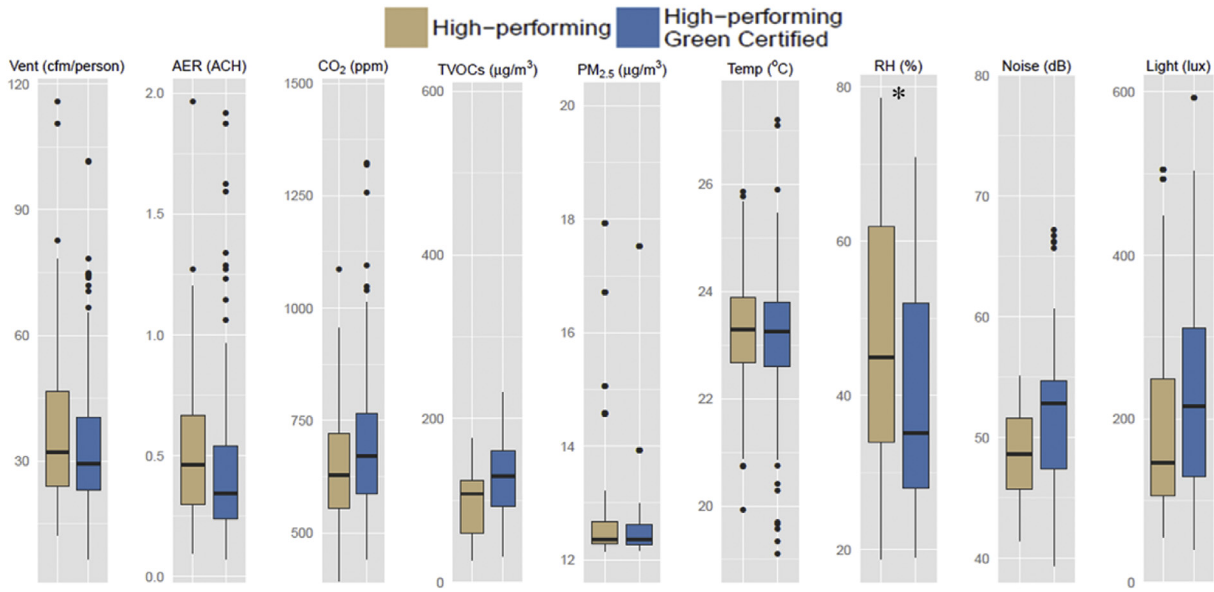


**Fig. 1.** Boxplots of indoor environmental quality (IEQ) parameters in high-performing, non-certified buildings and high-performing, green certified buildings. Vent, AER, $CO_2$, Temp, RH and Noise are measured by the Netatmo in every workstation each day, TVOCs are measured with summa canisters in 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.

ASHRAE Standard 55. After controlling for building classification, participants scored 5.4% higher on the cognitive tests, averaged across the nine domains of cognitive function, on days when they took the SMS test within the thermal comfort zone than when they took it without (Fig. 3). This finding is not statistically significant at the 95% confidence level.

**Table 2**
Demographic breakdown of participants in each building classification.

| | High-Performing Green Certified | High-Performing Non-Certified |
|---|---|---|
| *Number of Participants*[a] | 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% |

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

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 (Fig. 3).

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 (Fig. S2). These perceptions are linked to varying degrees to the monitored IEQ in the spaces. For example, relative humidities were 15.9% higher when participants reported the air was too humid and 9.3% lower when they reported the air was too dry. Importantly, for the same change in monitored IEQ conditions, participants in the green certified buildings report a larger improvement based on environmental perceptions. Lastly, participants in the non-certified buildings reported 0.5 (30%) more symptoms each day than those in the green certified buildings. Symptom counts are higher when participants report an issue with environmental conditions. Environmental perceptions and total symptom counts were not associated with cognitive function scores when introduced into the mixed effect models.

## 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

**Table 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[a] | Ventilation Strategy[b] | 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 | Pending | 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 | Pending | VAV, RC | 10 |

[a] EB = Existing Buildings, CI = Commercial Interiors.
[b] CV = Constant Volume, VAV = Variable Air Volume, SP = Single pass with energy recovery ventilator, RC = Partial recirculation with reheat.

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 µg/m3). 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 better environmental perceptions, 30% fewer sick building symptoms, 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. The reduction in self-reported symptoms and improvements in environmental perceptions support previous research in green buildings [23,24,27,30,42]. Participant's environmental perceptions do track actual IEQ conditions, but participants in green certified buildings are more likely to have a positive response even when IEQ conditions are the same. This observation, along with participants reporting more symptoms when they report problems with environmental conditions, highlights the limitations of using subjective metrics when assessing building performance or occupant wellbeing. For the cognitive function results, some of the domains that had the largest differences in scores (crisis response, information usage, and strategy) are the most highly correlated with other measures of productivity such as salary at age [36]. This aligns with Allen et al. that found these same domains to be the most impacted by $CO_2$, TVOCs and ventilation. By comparison, lowering TVOC concentrations from ~580 µg/m3 to ~40 µg/m3 caused a 61% increase in cognitive function scores in that study compared to 26.4% increase from working in a green certified building in this study.

While much of the effect of green certification on cognitive test scores is unexplained, the effect may be partly attributed to several IEQ parameters. 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 (Fig. S1). Participants outside this thermal comfort zone scored 5.4% lower on the cognitive simulations, but the finding was not statistically significant. The detriments to cognitive function align with previous research on

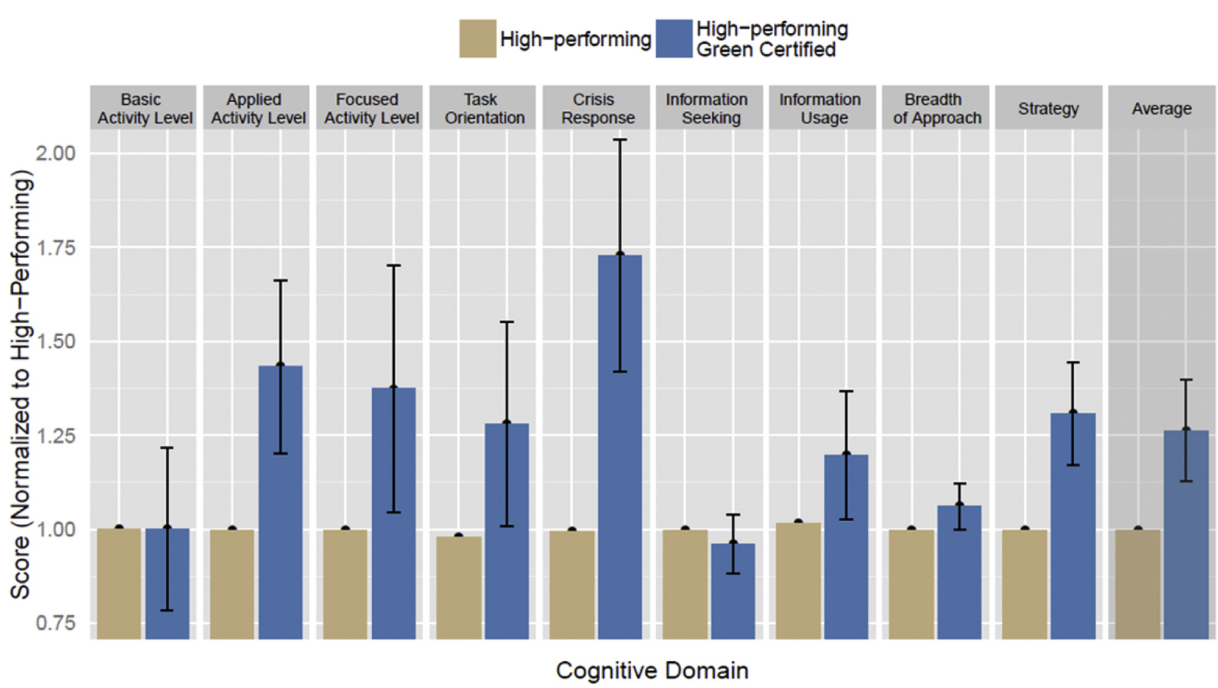


**Fig. 2.** Cognitive scores and 95% confidence intervals for each domain of the SMS tool after controlling for participant, normalized to high-performing buildings, for participants in high-performing and high-performing, green certified buildings.

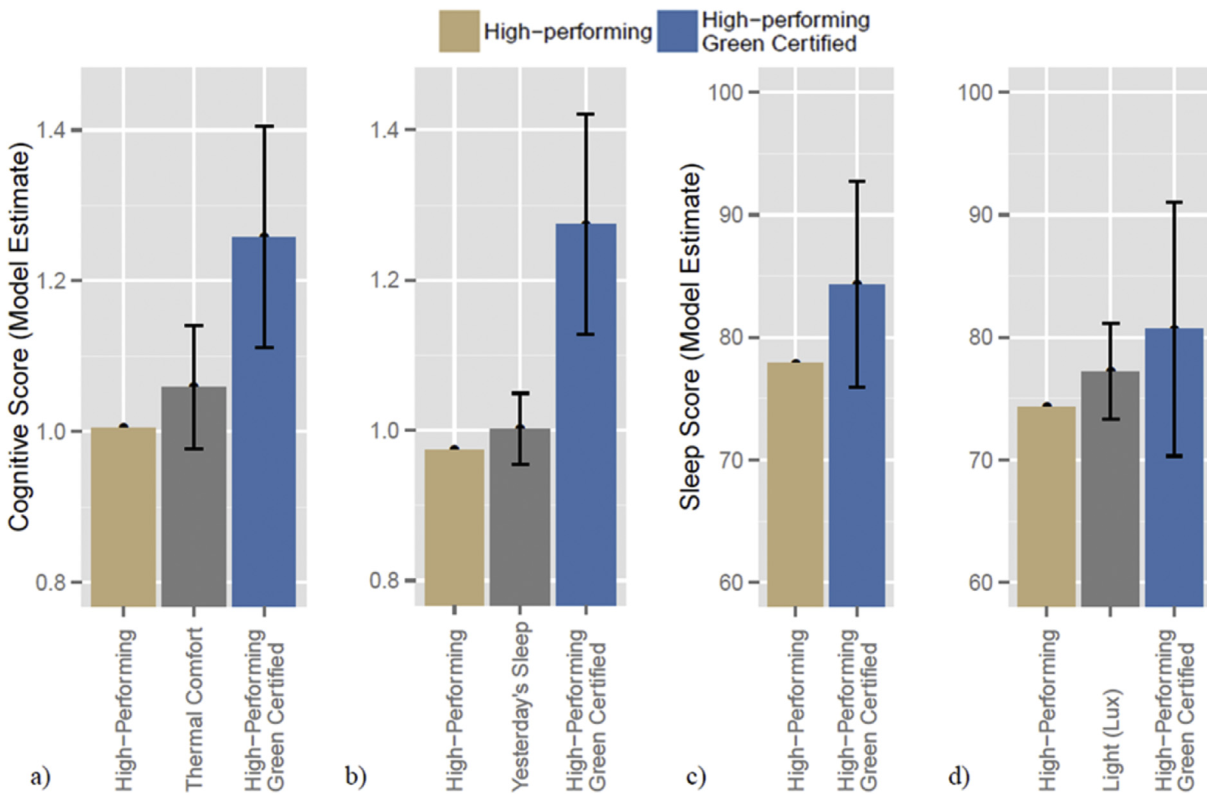


**Fig. 3.** Effect of **a)** thermal comfort on cognitive function scores, **b)** yesterday's sleep on cognitive function scores, **c)** building classification on Sleep Scores, and **d)** light levels on Sleep Scores, using generalized linear mixed effect models with 95% confidence intervals, treating 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.

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 [43]. The impacts on the SMS tool indicate that high order decision-making may also be affected by these exposures.

Not surprisingly, our study suggests that previous night's sleep is a driver of cognitive function scores. More interesting is that better Sleep Scores were 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 [44]. Similarly, a larger contrast between daytime light exposures and nighttime light exposures leads to a larger amplitude in daily melatonin secretion cycles [45]. 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 [46]. 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.

## 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. This outcome may be 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. Building-level factors may play an important role in occupant health and cognitive function yet have been largely overlooked. We describe the need for a holistic, "buildingomics" approach to studying the drivers of human health and performance in buildings.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.buildenv.2016.11.041.

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