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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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Short running title: Green buildings and cognitive function

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ABSTRACT

Background: The indoor built environment plays a critical role in our overall well-being, 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.

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.

METHODS

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.

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). 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.

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.

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 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.

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 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).

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 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.

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 4).

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).

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 5), Green (Figure 1) or Green+ (Figure 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).

RESULTS

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 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). 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 5).

The raw cognitive scores for each domain were normalized to the conventional condition and modeled by study day controlling for participant (Table 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 5 with the Green condition as the reference category (data not shown).

The model of the average scores in Table 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.

Carbon Dioxide and Cognitive Function

The effect of CO_2 on cognitive function scores, while holding all other parameters constant, is depicted in Figure 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 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 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 2).

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 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.

DISCUSSION

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 μg/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 μg/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 μg/m^3 and the BASE mean concentration of 450 μg/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.

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.

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 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.

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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Table 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

Table 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 (μg/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 (^{o}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 (μg/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 (μg/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
$PM_{2.5}$ (μg/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.

Table 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

Table 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

Table 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 [1.28,1.43] (<0.0001)	1.39 [1.26,1.52] (<0.0001)	1.44 [1.27,1.62] (<0.0001)	1.14 [1.11,1.17] (<0.0001)	2.35 [1.91,2.78] (<0.0001)	1.10 [1.07,1.14] (<0.0001)	3.94 [3.47,4.41] (<0.0001)	1.43 [1.25,1.60] (<0.0001)	3.77 [3.40,4.14] (<0.0001)	1.99 [1.89,2.09] (<0.0001)
Moderate CO_2	1.20 [1.13,1.27] (<0.0001)	1.08 [0.95,1.21] (0.23)	1.68 [1.51,1.85] (<0.0001)	1.05 [1.02,1.08] (0.0009)	2.05 [1.63,2.48] (<0.0001)	1.11 [1.08,1.15] (0.61)	2.61 [2.15,3.07] (<0.0001)	1.29 [1.12,1.46] (0.0013)	3.17 [2.81,3.53] (<0.0001)	1.69 [1.59,1.79] (<0.0001)
High CO_2	0.91 [0.84,0.98] (0.015)	0.88 [0.75,1.01] (0.081)	0.85 [0.68,1.02] (0.087)	1.00 [0.97,1.03] (0.76)	1.33 [0.90,1.75] (0.14)	1.08 [1.05,1.12] (0.35)	1.01 [0.55,1.48] (<0.0001)	0.98 [0.81,1.15] (0.78)	0.83 [0.47,1.19] (0.36)	0.99 [0.89,1.09] (0.78)
Green	1.14 [1.06,1.21] (0.0003)	1.04 [0.91,1.18] (0.51)	1.51 [1.34,1.68] (<0.0001)	1.03 [1.00,1.06] (0.065)	1.97 [1.54,2.40] (<0.0001)	1.09 [1.05,1.12] (0.45)	2.72 [2.26,3.19] (<0.0001)	1.21 [1.04,1.38] (0.018)	2.83 [2.46,3.19] (<0.0001)	1.61 [1.51,1.71] (<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 [1.30,1.44] (<0.0001)	1.33 [1.20,1.46] (<0.0001)	1.52 [1.35,1.69] (<0.0001)	1.15 [1.12,1.19] (<0.0001)	2.27 [1.85,2.69] (<0.0001)	1.11 [1.08,1.15] (<0.0001)	4.04 [3.58,4.51] (<0.0001)	1.50 [1.33,1.67] (<0.0001)	3.98 [3.62,4.34] (<0.0001)	2.03 [1.93,2.13] (<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

FIGURE LEGENDS

Figure 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.

Figure 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.

Figure 1.

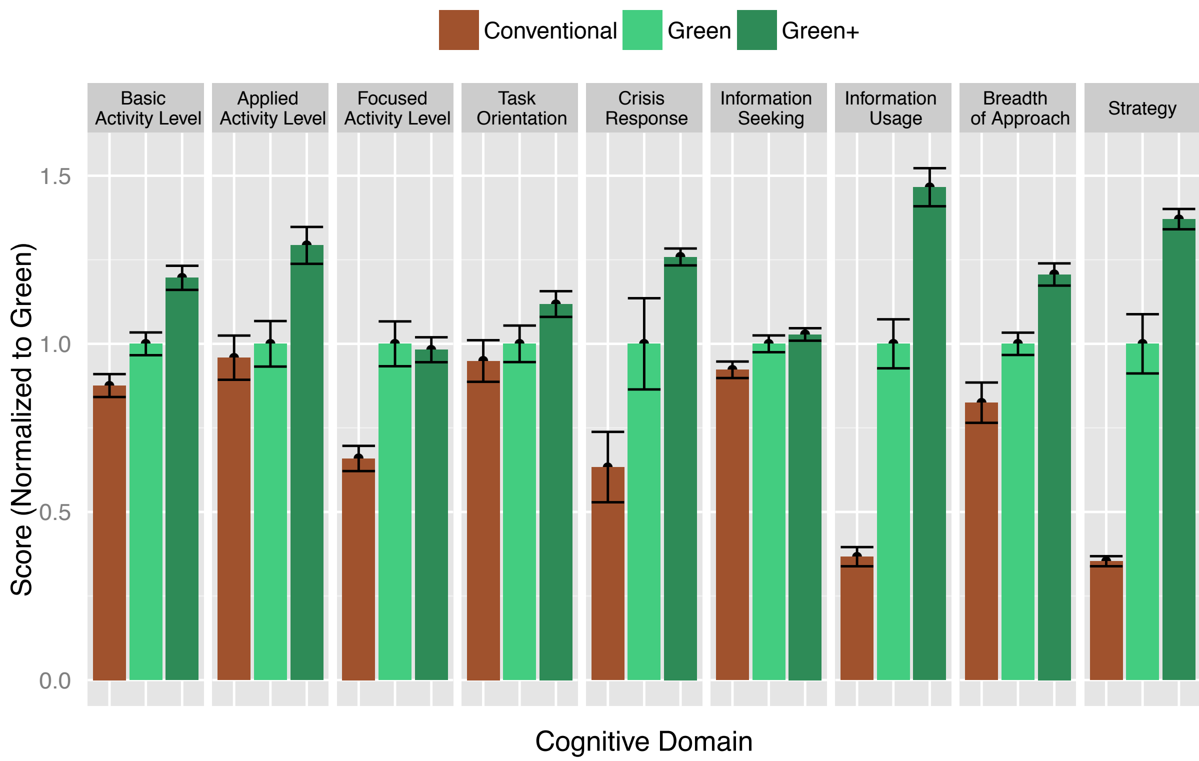
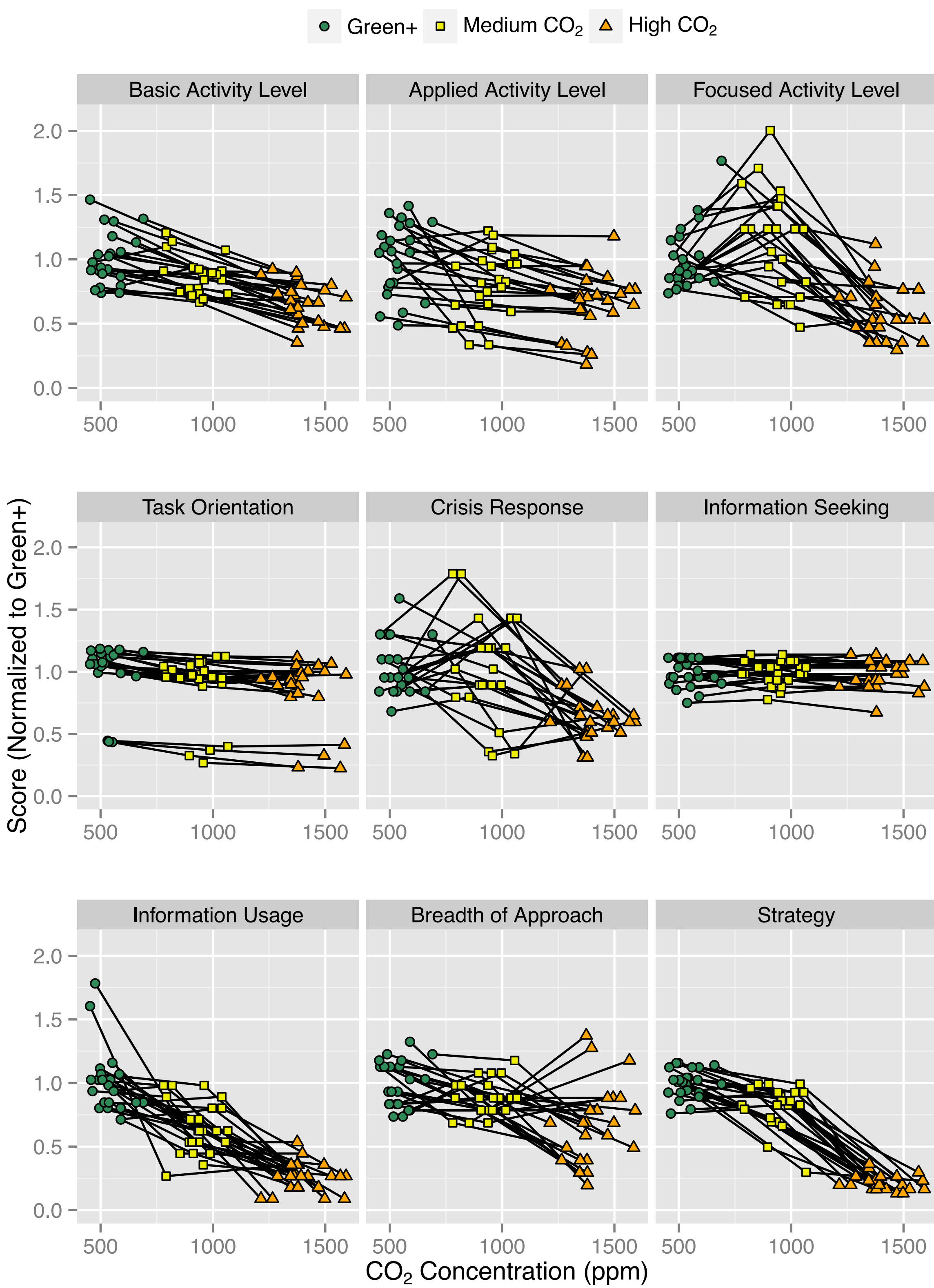

Conventional
Green
Green+
Basic Activity Level
Applied Activity Level
Focused Activity Level
Task Orientation
Crisis Response
Information Seeking
Information Usage
Breadth of Approach
Strategy
Score (Normalized to Green)
1.5
1.0
0.5
0.0
Cognitive Domain

Figure 2.


Green+
Medium CO_2
High CO_2
Basic Activity Level
Applied Activity Level
Focused Activity Level
Task Orientation
Crisis Response
Information Seeking
Information Usage
Breadth of Approach
Strategy
Score (Normalized to Green+)
CO_2 Concentration (ppm)
0.0
0.5
1.0
1.5
2.0
500
1000
1500