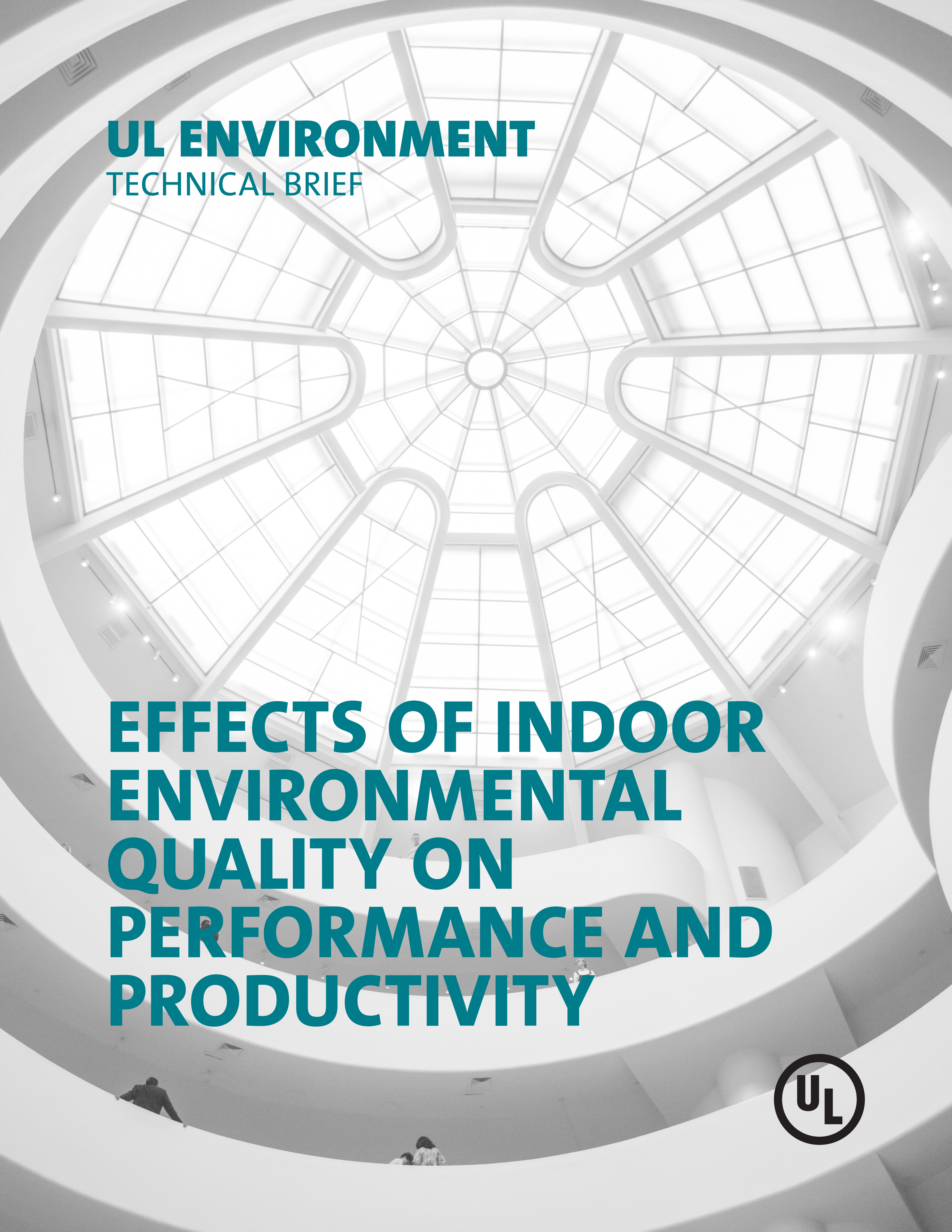


UL ENVIRONMENT
TECHNICAL BRIEF

EFFECTS OF INDOOR ENVIRONMENTAL QUALITY ON PERFORMANCE AND PRODUCTIVITY

Effects of Indoor Environmental Quality on Performance and Productivity

Introduction

In the developed world, humans spend about 90% of their time indoors.(EPA, 1989) That time is spent sleeping, working, attending school, cooking, eating, and all related tasks. In the last 150 years, the indoor environment has changed dramatically, from soot and dust filled rooms lit by candles and heated by wood or coal to the modern office and residential spaces with state of the art materials and invisible systems to provide heat, cooling, humidity control, and particle filtration. Since we spend so much time indoors, it is in our best interest that the environments we create for working and learning are designed to maximize productivity and performance, or at the very least, minimize the negative effects these spaces may incur on the inhabitant.

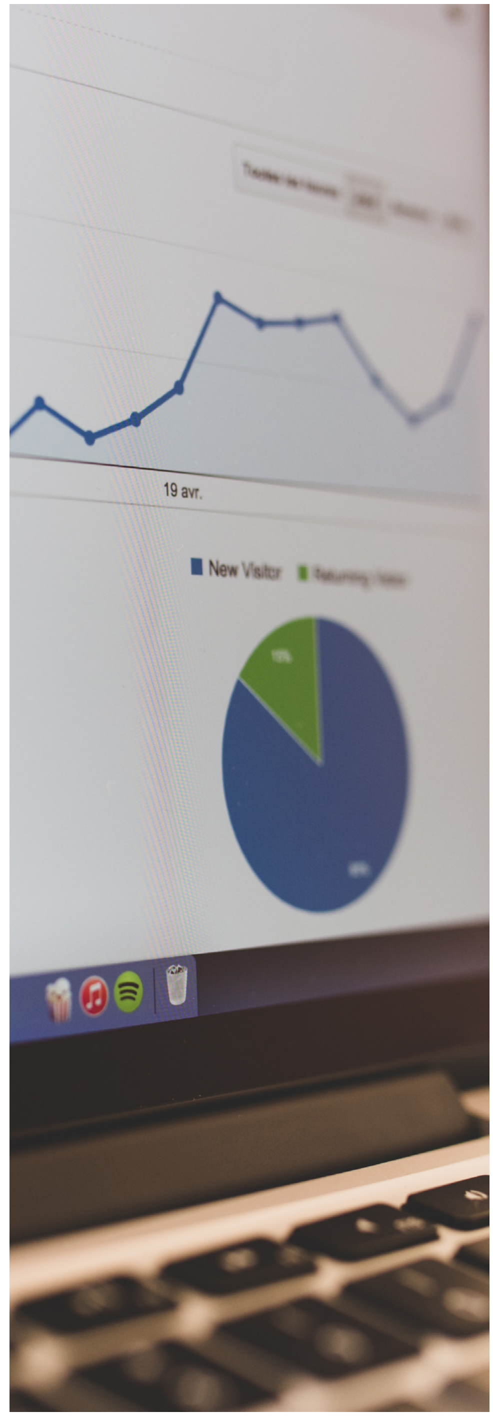
Over the past 50 years, there has been a growing body of research surrounding optimal indoor conditions. This research has been conducted from several fronts: architects and designers tweaking indoor plans to make spaces aesthetically pleasing, mechanical engineers modifying designs of heating, ventilation, and air conditioning (HVAC) equipment to make spaces more comfortable, and environmental health practitioners performing studies of different indoor environment pollutants and their effects on occupants.

Today, 14 percent of healthcare costs are driven by conditions related to Indoor Environmental Quality (IEQ), including asthma and allergies; headaches; respiratory disease; eye, nose and throat irritation; reproductive and developmental defects; neurological disease; cardiovascular disease; and some forms of cancer. Poor IEQ in commercial buildings can lower worker productivity, while conversely improving IEQ can significantly reduce absenteeism and improve productivity. (Underwriters Laboratories, 2014)

This report is an attempt to summarize the main tenets linking IEQ and human performance and productivity.

Both the exposure (IEQ) and outcome (performance/productivity) are defined differently depending on the source. According to the National Institute for Occupational Safety and Health (NIOSH), "Indoor environmental quality (IEQ) refers to the quality of a building's environment in relation to the health and wellbeing of those who occupy space within it. IEQ is determined by many factors, including lighting, air quality, and damp conditions."(NIOSH, 2015) The complexity of environmental parameters is also complex, as "building occupants may be exposed to a variety of contaminants (in the form of gases and particles) from office machines, cleaning products, construction activities, carpets and furnishings, perfumes, cigarette smoke, water-damaged building materials, microbial growth (fungal, mold, and bacterial), insects, and outdoor pollutants. Other factors such as indoor temperatures, relative humidity, and ventilation levels can also affect how individuals respond to the indoor environment."(NIOSH, 2015) Performance is also not an exact variable, as it may be calculated via speed of work, quality of work, presence or lack of respiratory symptoms, or absenteeism. Also, evaluating work performance is useful because the monetary costs can be extrapolated from increased productivity of occupants. (Seppanen, Fisk, & Lei, 2006) In addition, it seems like in the last several years, there has been a coalescing of thought around how to measure performance objectively, in an attempt to control for different indoor environment variables.

In this brief, we focus mostly on research into performance metrics related to IEQ in office environments. We will discuss different components of Indoor Environments that have been studied, and introduce recent research that appears to be a major breakthrough in the field related to Carbon Dioxide (CO_2) levels.



How do you measure performance?

The available literature suggests that performance can be measured in a variety of ways, depending on the subject population and the type of study being conducted. For instance, several studies used the concept of Disability Adjusted Life Years (or DALYs) which are defined by the World Health Organization as "years of healthy life lost". (Allen et al., 2015; Chan, Parthasarathy, Fisk, & McKone, 2015; Logue, Price, Sherman, & Singer, 2012) DALYs are calculated by summing the Years of Life Lost (which depends on both the number of early mortalities and lost life expectancy attributable to the early mortalities) and Years of Life Disabled (which depends on the number of incident cases of disability, length of the case and its disability weight). Other studies have evaluated speed of task completion (with metrics such as calls answered per hour in a call center, or typing speed), symptoms of Sick Building Syndrome (headaches and respiratory irritation) and absenteeism.

Several studies have also examined the relationship between outdoor pollution and worker/student productivity, measuring work output or cognitive ability in the presence of ambient air pollutants like ozone, NOx, and radiation. (Almond, Almond, & Edlund, 2007; Lavy, Ebenstein, & Roth, 2012; Zivin & Neidell, 2011) Subjects are also often asked to provide subjective assessments of their performance, however this has been shown to not be a reliable source of data.(Wyon, 2004)

Based on the current literature, using an objective measurement of performance is ideal for assessing performance, so that limited bias is introduced. Several studies used the Strategic Management Simulation (SMS) software tool, which asks participants to respond to several situations with strategic thinking, scoring them in several different cognitive factors such as Information Seeking, Strategy, and Task Orientation. The SMS tool has been proven effective in a variety of exposure scenarios, such as caffeine, antihistamines, alcohol, marijuana, and tranquilizers. (Satish, Cleckner, & Vasselli, 2013)

Which components of the Indoor Environment affect Performance?

The most studied components of the Indoor Environment related to occupant performance are Ventilation, Temperature, VOCs, and CO_2. In the following pages, I will break out each of these parameters and its function on performance.

Ventilation Rates and Performance

One of the more obvious metrics of IEQ and performance is ventilation rates. Ventilation is typically measured in Liters per second per person (L/s-person). Most studies have shown a positive direct relationship between increased ventilation and productivity of occupants. Specifically, greater percentages of fresh, outdoor air are critical for this relationship to hold.

A meta-analysis performed in 2005 found that there was a 1-3% improvement in productivity for each additional 10 L/s-person of ventilation, from approximately 6.5 L/s-person up to 65 L/s-person. (Seppanen et al., 2006) Ventilation rates as a function of performance with a baseline of 6.5 L/s-person are plotted in Figure 1 below.

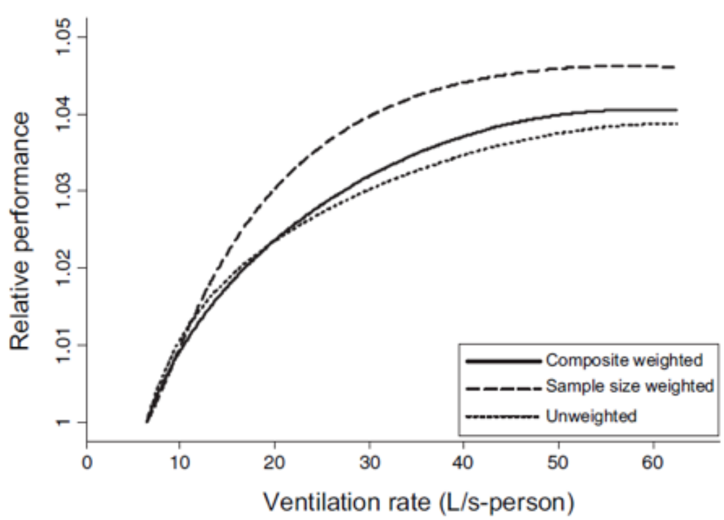
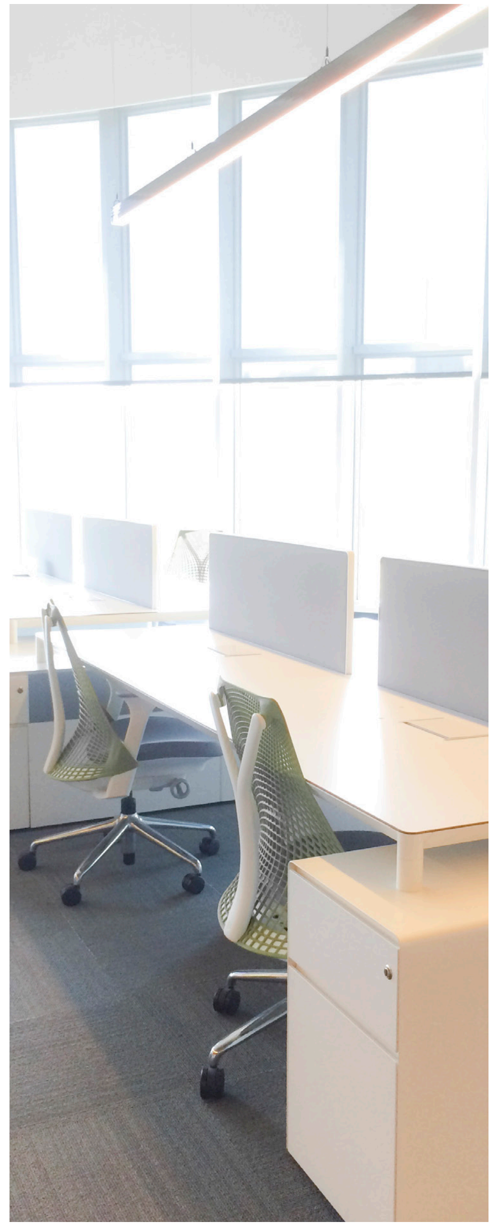


Figure 1: Relative performance in relation to the reference value 6.5 L/s-person versus average ventilation rate (Seppanen et al., 2006)

In 2013, Chan et al. provided a risk assessment for chronic exposure to volatile organic compounds (VOCs) and particulate matter (PM2.5) as a function of ventilation rates. They modeled results from previous studies connecting ventilation and concentrations of these two pollutants at 0.5x and 2x ventilation rates. They then compared the results to regulatory agency data on chronic health risks. The results of the modeling are rather intuitive: doubling ventilation rates significantly reduced the VOC concentrations and resulting modeled chronic health effects, but higher ventilation rates also increased the amounts of PM2.5 exposure (since much of PM2.5 matter is generated from outdoor air). In addition, it appears that filtration is the best solution for PM2.5 loads, independent of the ventilation rates.(Chan et al., 2015)



The American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) first published ASHRAE Standard 62 in 1973. ASHRAE Standard 62 has been modified in the decades since, but it remains among the most prominent and most cited documents on ventilation. The standard lists minimum ventilation requirements for a variety of indoor spaces. The first version of Standard 62 included the purpose statement “minimum and recommended air quantities for the preservation of occupants’ health, safety, and well-being”. This statement was controversial within ASHRAE almost immediately, as many members felt that as an engineering society, ASHRAE should not be involved in occupant health. (Persily, 2015) The statement evolved over the subsequent years, and the board of directors ultimately approved a rule that IEQ and ventilation standards “shall not make any claims or guarantees that compliance will provide health, comfort or occupant acceptability, but shall strive for those objectives ...” and that “ASHRAE standards shall consider health impacts where appropriate.” (ASHRAE, 2014; Persily, 2015) The evolution of Standard 62 demonstrates the changing understanding of the relationship between ventilation rates and indoor environmental quality.(Allen et al., 2015)

Ventilation is one of the more discussed issues related to building mechanical system operation, as increased outdoor air ventilation comes with higher energy loads and therefore higher costs, and it has been shown that increased ventilation often leads to positive health outcomes for occupants.

Temperature and Performance

Indoor air temperature is one of the most noticeable aspects of any workplace or other building. Studies on the relationship between temperature and worker performance have been conducted since at least the 1920's. Early studies found a marked relationship between temperature and manual work (i.e. factories, mills, etc.). However, the correlation between temperature and mental work is more complex. A summary conducted in 1997 found that for some types of mental work, such as complex and creative tasks, optimal performance coincides when the occupants are at optimal thermal comfort. However, other types of mental work are best completed under slightly cooler temperatures. The conclusion was that performance may be increased by giving occupants individual control of local temperature settings. (William J. Fisk & Rosenfeld, 1997)

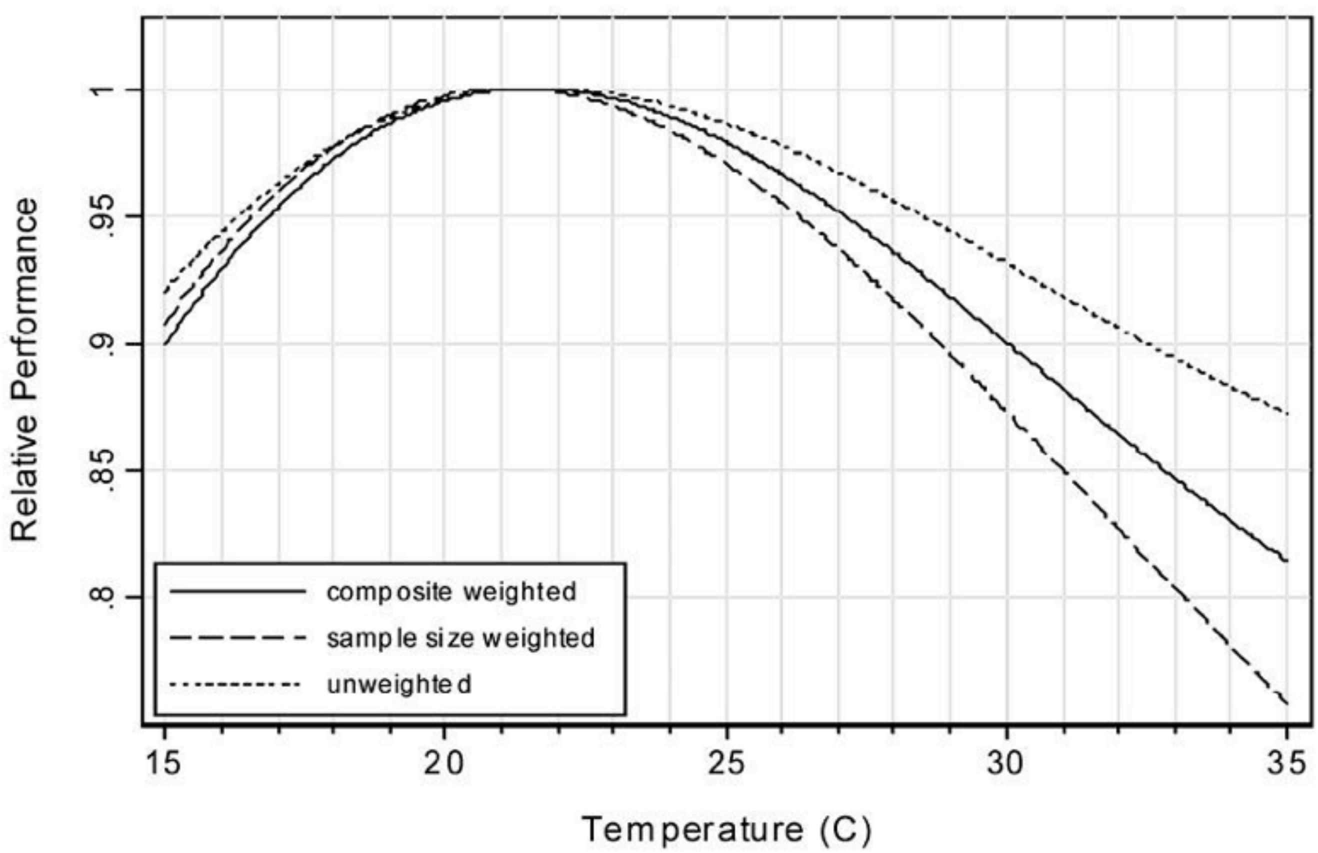


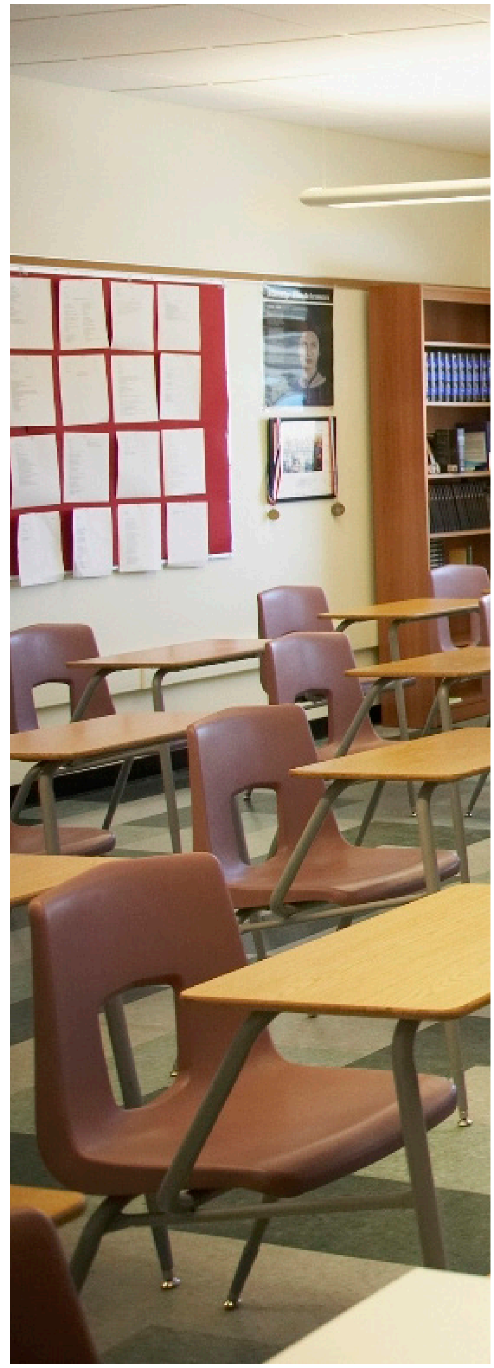
Figure 2: Relative performance versus Temperature (maximum performance is set to 1) (Seppanen et al., 2006)

VOCs and Performance

A consequence of spending so much time indoors is that the majority (more than 70%) of chemical exposures happen there. (Gokhale, Kohajda, & Schlink, 2008) Volatile Organic Compounds (VOCs) are emitted gases from certain solids or liquids. They emit from many different sources commonly found within homes and offices, including paints, aerosol sprays, cleaners, air fresheners, fuels, dry cleaned clothing, pesticides, building materials/furnishing, and office equipment such as copiers, glues, and markers. (EPA, 2015)

Studies have been conducted on exposure to VOCs emitting from paints, building materials, and other sources, showing a correlation between higher concentrations of VOCs and lower performance. A 2013 study even showed that a freshly painted room impaired the cognitive ability of occupants in a similar way to alcohol. (Satish et al., 2013) Recent research also shows that at lower levels, VOC concentration may effect decision making as well. It is not clear which VOCs are the most detrimental to performance; researchers believe that there are different VOC combinations that affect individuals uniquely, but more study on this topic is needed. (Stromberg, 2014)

In an office environment, the majority of the VOC load comes from building materials and cleaning products. Low VOC variations of these products are a significant part of high performance building systems such as the LEED standard, Living Building Challenge, and WELL, which have all recognized the need to reduce VOC exposure in general to improve occupant health and performance.



Carbon Dioxide and Performance

One of the most widely used metrics for measuring ventilation is CO_2 concentration in the space. Scientists have used CO_2 as a representative gas, and correlate that level to higher levels of VOCs, microbial contaminants, and allergens. However, recent research questions whether CO_2 itself is leading to occupant performance reduction.

The current Standard 62 guideline for CO_2 is 1,000 ppm above outdoor levels. But as discussed above, Standard 62 is first and foremost an engineering standard, rather than a health based one. As Persily pointed out, "CO_2 limits in ventilation standards are related to recommended ventilation rates for body odor control under idealized, steady-state conditions, not to the health or comfort impacts of the CO_2". (Persily, 2015)

William Fisk of Lawrence Berkeley National Laboratory stated, “We've known for a long time that higher carbon dioxide levels were statistically correlated with reduced performance, but we assumed it was a proxy for other pollutants that varied with ventilation rates. That's basically been the dogma."(Stromberg, 2014) We also know that high levels of CO_2 can be detrimental to humans: acute exposure to 50,000 ppm leads to signs of intoxication, 100,000 ppm can cause unconsciousness, and exposure to 250,000 ppm can cause death. (Lipsett, Shusterman, & Beard, 1994) But until 2012, research was not being done on CO_2 concentrations that were conceivable in crowded rooms like elementary school classrooms. (2,500-3,000ppm)

Three studies since 2012 have started a shift in how the scientific community views CO_2 in relation to performance. The first was conducted in 2012 by a group from Budapest University of Technology and Economics, which found that spending a few hours in a chamber with CO_2 levels of 3,000 ppm made it difficult to concentrate.(Kajtár & Herczeg, 2012)

Lawrence Berkeley National Laboratory (LBNL) and SUNY Upstate Medical University performed a study in 2012, in which participants were subjected to different levels of CO_2 for 2.5 hour intervals in an attempt to see how the different concentrations affected decision making skills. 22 participants were exposed to CO_2 at 600, 1000, and 2500 ppm, and at the end of each period took a test (the SMS test discussed earlier) measuring decision making performance, health symptoms, and perceived air quality. This study found that relative to the 600 ppm level, performance on 6 of 9 scales was reduced moderately at 1000 ppm, and performance on 7 of 9 scales was greatly reduced at 2500 ppm. While concentrations approaching 2500 ppm are rarely seen in most office environments, a study of elementary schools in Texas showed that a substantial number exhibited concentrations above 2000 ppm. (Corsi, Torres, Sanders, & Kinney, 2002)

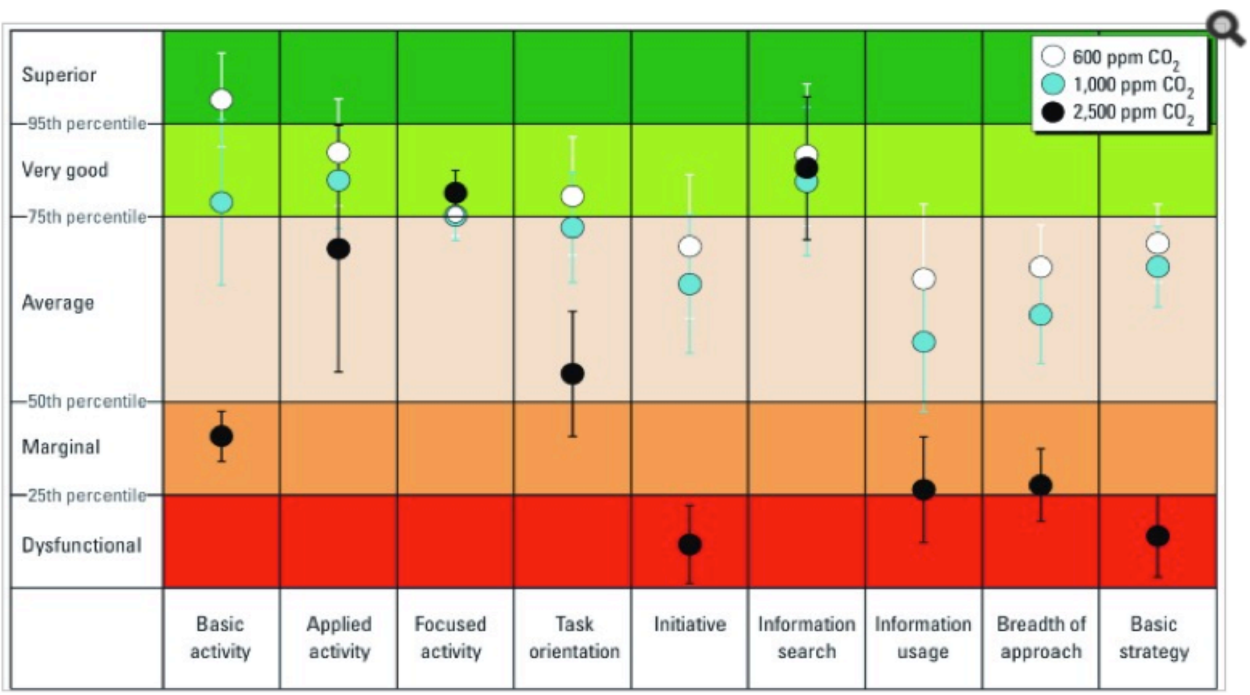


Figure 2: Impact of CO_2 on human decision making performance. Error bars indicate 1 SD.
(Satish, et al. 2012, Environmental Health Perspectives, http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3548274/

In 2015, researchers from the Harvard School of Public Health, SUNY Upstate Medical School, and Syracuse University authored a paper examining the association between CO_2, Ventilation, and VOC exposure and cognitive function scores. This study was designed to build off the findings from the LBNL study to include different building types (high performance and typical), longer exposure times, and blinded participants, among other changes. In the study, 24 participants worked for 6 days in a mocked up office, where minimum ventilation standards as defined by ASHRAE were implemented. On each of the 6 days, the rates of ventilation, Total VOC, and CO_2 levels were set in different combinations, to which the participants were blinded. Building types were divided between "Conventional", "Green" (low VOC) and "Green +" ("Green" with higher ventilation rates). On two of the study days, the authors also changed the amount of CO_2 in the space, holding all other variables (ventilation and VOC concentration) constant. CO_2 concentrations varied from 550 ppm to 1400 ppm.

Each day, participants completed the SMS test, which computed scores for 9 cognitive factors. On average, cognitive scores for were 61% higher on "Green" days and 101% higher on "Green +" days.

Three areas showed the largest improvements: crisis response, information usage, and strategy. Crisis responses were 97% higher in the "Green" environment and 131% higher in the "Green +" environment compared to conventional buildings. Information usage scores were 172% and 299% higher, respectively. Scores "Green" and "Green +" buildings were 183% and 288% higher than the conventional building scenario.

Costs/Benefits

Buildings account for more than 40% of US energy consumption, with nearly half of that coming from commercial buildings. In office buildings, more than half of the energy costs are attributable to heating, ventilating, and cooling. (EIA, 2008, 2015) Therefore, building managers are incentivized to reduce energy wherever possible, which is often accomplished by reducing ventilation rates.

In the 1970s, increasing energy prices led to a change in the way buildings were constructed and operated in the United States. Buildings were built to be more air tight and energy efficient, and ventilation requirements were relaxed to conserve energy in the 1980s. Around the same time, building related illnesses and Sick Building Syndrome (SBS) were first reported. (Riesenberg & Arehart-Treichel, 1986)

While it is helpful to have scientific literature on the indoor environment's influence on occupant performance, the costs and benefits must be weighed before these changes are implemented in the real world. As Fisk et al found in a study from 2011, "estimates [of benefits], particularly the monetary estimates, also facilitate the communication of the importance of IEQ to policy makers, building professionals, and the broader public."(W. J. Fisk, Black, & Brunner, 2011)

Studies have consistently shown that increased productivity does outweigh the costs of increased energy usage in a building.

Table 1: Estimated potential productivity gains from improvements to indoor environments (Fisk & Rosenfeld, 1997)

Sources of Productivity Gain	Strength of Evidence	Potential U.S Annual Savings or Productivity Gain (1993 $U.S)
Reduce respiratior disease	Strong	$6-$19 billion
Reduce allergies and asthma	Moderate	$1-$4 billion
Reduce sick building syndrome symptoms	Moderate to Strong	$10-$20 billion
Improve worker performance: From changes in thermal environment From changes in lighting	 Strong Moderate	 $12-$125 billion

In 2015, the authors of the Harvard study also evaluated the results of their previous study in cost/benefit terms. They found that doubling the ventilation rate would cost less than $40 per person per year in all climate zones investigated, and would improve the performance of workers by 8%. This was equated with a $6,500 increase in employee productivity per year. (MacNaughton et al., 2015) They also updated the numbers presented in table 1, approximating the annual savings of $125 billion in 1993 dollars is roughly $186 billion in 2015 dollars. They also estimated that even with conservative estimates, the increased productivity of an employee is more than 150 times higher than the energy costs associated with increasing ventilation. (MacNaughton et al., 2015)

Conclusion

Based on the body of current research, it is clear that the productivity of workers is becoming more easy to measure, and the benefits of improved IEQ are becoming more obvious to policy makers, building managers, and companies occupying those buildings. It is important to note that as building envelopes become tighter, the energy required to ventilate the space effectively will be reduced. This allows for a future of buildings that are more energy efficient and healthier for the workers that occupy them. In the same way that Total Worker Health programs are moving away from merely preventing accidents to providing healthy spaces for employees, building managers and engineers should heed the research of the last 10 years showing a clear need to optimize indoor environmental conditions for occupants.

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