THE NATURE OF AIR

ECONOMICS OF INDOOR AIR QUALITY AND BIO-INSPIRED INNOVATION

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CO-AUTHORS

Dakota Walker Terrapin Bright Green
William Browning Terrapin Bright Green

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Terrapin Bright Green LLC
New York NY | Washington DC
www.terrapinbrightgreen.com
biophilia@terrapinbg.com

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Biological systems are a source of creative inspiration that can inform building design and function. To this end, nature can be reinvisioned not as a force to be tamed, but as a knowledge source and goalpost for designers and engineers alike. Underpinning this shift is a demand for an environmentally mindful building that supports the psychological and physiological needs of occupants. Indoor air quality management remains an industry challenge as efforts to improve air quality, and subsequent occupant wellness, often come at the expense of energy performance. Insights from atmospheric cleaning mechanisms have spurred the development of air purifying technology to realign air quality management with the fundamental processes found in nature.

Image Credit: Simon Migaj / Pexels

THE AVERAGE ADULT BREATHES IN APPROXIMATELY

11,500 LITERS

OF AIR PER DAY.[2,3,A]

OF ALL THE PARTICLES WE INHALE

25-60%

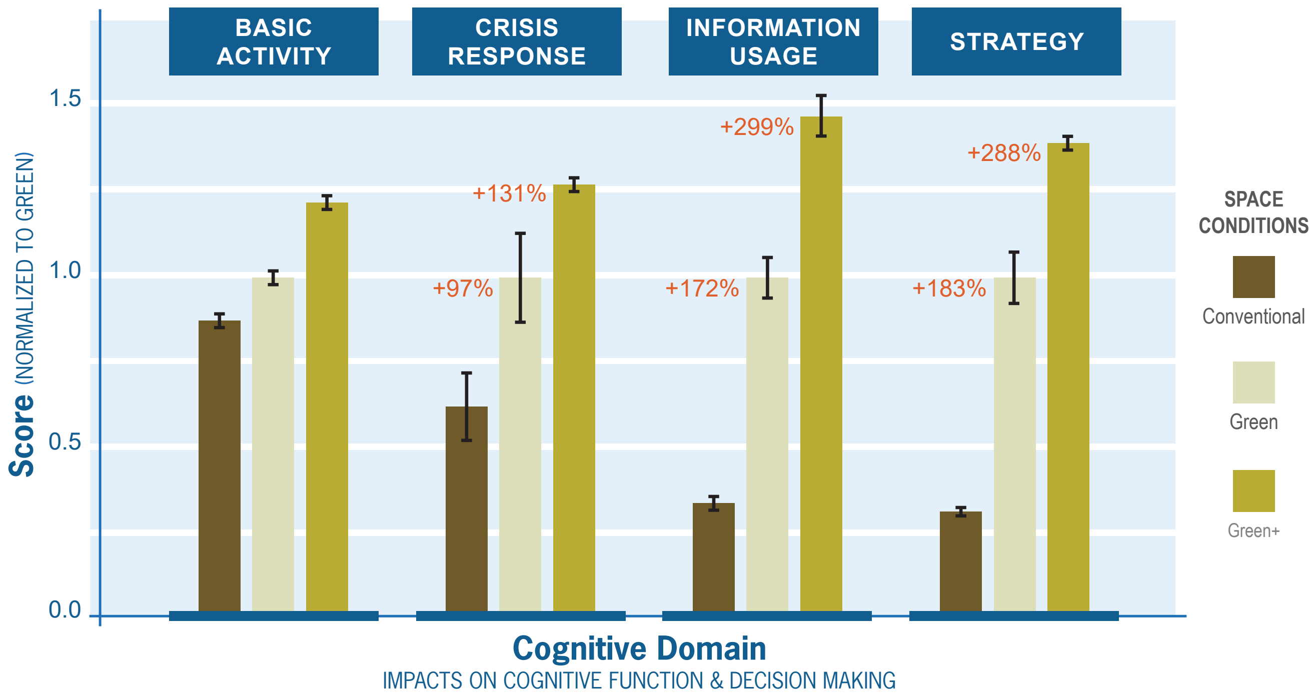
ARE DEPOSITED IN OUR RESPIRATORY SYSTEM.[4]

Air and space are synonymous in most people's understanding of indoor environments. More often than not, this 'void' contains a potent mixture of microbial contaminants, fine particulate matter (PM) and volatile organic compounds (VOCs). Indoor air quality (IAQ) is typically diminished on two fronts: outdoor pollutants brought in through ventilation and occupant ingress, and indoor pollutants emerging from the very materials and furnishings that make up a building. Despite attempts to improve indoor air with better filters and airtight building envelopes, more than two-thirds of indoor and outdoor air quality studies find higher air pollutant concentration indoors than outdoors.[1]

Although air pollutants may not be consciously perceived by occupants, their detriment to health and wellbeing is well documented. Comparative risk assessment studies by the Environmental Protection Agency (EPA) have consistently ranked poor indoor air quality among the top five environmental dangers to public health.[5,6] The most commonly reported symptoms associated with poor indoor air quality include headaches, fatigue, trouble concentrating, and irritation of the eyes, nose, throat and lungs.[7] Studies have also linked long-term air pollutant exposure to impaired memory, degraded cognitive performance, disrupted sleep, increased rates of asthma, heart disease, and certain cancers.[8,9]

ECONOMICS OF POOR INDOOR AIR QUALITY

In the workplace, poor air quality impairs the ability of employees to perform at their best, which diminishes productive value of salaries and benefits. A 2016 study conducted by the Harvard T.H. Chan School of Public Health, SUNY Upstate Medical University, and Syracuse University, found a significant correlation between cognitive performance and indoor air quality. Testing nine proxies for cognitive functioning against three air quality indicators (VOC concentration, CO_2 concentration, and ventilation rate), researchers found an average cognitive score increase of 61% for simulations of "green buildings" (low-VOC and moderate CO_2) and 101% for "green+ buildings" (low-VOC and low CO_2), as compared to conventional offices (high VOC, high CO_2). Researchers found the greatest difference in cognitive performance during tests of crisis response, strategy, and information usage.[10] Furthermore, as a more direct analysis of employee productivity, Wargocki, Wyon, and Fanger



estimated a 1.9% increase in office task performance for every two-fold decrease of the pollution load.[11]

Employees are by far the largest investment in a company's operating costs. Per square foot, a company spends almost 20 times more on employees than on rent and energy costs combined.[12,13,14,B] A company's return on employee investment is a function of workplace productivity. Increases in sick days taken, breaks due to fatigue, or slower office task performance translate into lost company revenue and can add up to considerable sums. For instance, the aforementioned correlation between IAQ and office task performance can be used to translate poor air quality into dollars lost. A four-fold discrepancy in air quality between comparative buildings would yield a 3.8% difference in office task performance. In a typical office of 100 employees, unproductive time due to poor IAQ would thus contribute to $326,496 in wasted salary and benefit expenditures annually.[11,12,C]

Conventional strategies to improve indoor air quality and reduce energy consumption often conflict. In a typical large office building, fan power for ventilation is approximately 10% of total energy consumption—not accounting for energy to heat and cool newly introduced, outside air, which comprises another 34%.[15] Filters, too, carry an energy price. A recent report by the design firm, Gensler, found that air pollutant filtration

IMPACT OF IAQ ON COGNITIVE PERFORMANCE

Cognitive performance is often measured as the aggregate of myriad mental processing domains. In the Harvard coalition study, participants were subjected to nine separate cognitive functioning tests in offices of differing air quality. The chart includes results from four cognitive tests, showing increased performance in Green and Green+ offices. Data is normalized to the "Green" condition by dividing all scores by the average score during the "Green" condition.

Data Source: Allen et al. (2016). Associations of Cognitive Function Scores with Carbon Dioxide, Ventilation, and Volatile Organic Compound Exposures in Office Workers. *Environ. Health Perspectives, 124*(6).[10]

systems increase energy use by approximately 7% in commercial office buildings.[16] While the cost savings associated with worker productivity improvements far outweigh increased energy costs of fan-power or air filters, in the long run emissions associated with increased energy use only exacerbate those pollutant loads that ventilation systems are tasked with abating.

Competing outcomes—in this case, energy-efficiency and wellbeing—often indicate a more systemic design problem. Some engineers have turned to nature for insight, asking how buildings can control indoor air pollutants without flushing temperature- and humidity-conditioned air, and how they might instead condition the molecular composition of air to address air pollutants that eminate from both inside and outside.

INSPIRATION FROM NATURE

When imagining clean, rejuvenating air, one might conjure visions of high mountain-tops or misty waterfalls—in other words, pristine nature. In reality, plants, animals, and even underlying geology pose numerous challenges to air quality whether from airborne particulate matter, pollen, mold, bacteria or noxious gasses. Despite these many natural pollutants, Earth's troposphere—the bottom layer of atmosphere—has remained clean, intact, and molecularly balanced over the hundreds of millions of years it has existed in this particular state of dynamic

AGGLOMERATION

Snowflakes are a product of ice crystal agglomeration. Ice crystals build up, become heavier than air, then precipitate to the ground. This same principle applies to dust agglomeration via air ions.

Image Credit: Marc Newberry / Unsplash

STERILIZATION

Bacteria, like E. Coli *shown above, are neutralized when air ions pull hydrogen molecules away from the cell wall, dehydrating the cell and hindering its ability to interact with other organisms.*

Image Credit: Eric Erbe, USDA / Wikimedia commons

OXIDATION

The iconic green patina on the Statue of Liberty is not original. It formed naturally over time from the same chemical process that breaks down VOCs and other noxious gasses in the atmospehere.

Image Credit: Brandon Mowinkel / Unsplash equilibrium. Utilizing only ambient energy and basic tenets of physics and chemistry, the mechanisms by which the atmosphere remains clean exemplify principles of circularity, synergy, and resource efficiency. Most of these cleaning mechanisms initiate from an interaction between the atmosphere and something else (plants, soils, oceans, rainfall), but arguably the most important atmospheric cleaning process is carried out by the atmosphere itself.

Tropospheric air ions support the mechanism by which the atmosphere can self-regulate air pollutants. Ions, any element or molecule that is charged via loss or gain of electrons, facilitate atmospheric cleaning in three main ways. **Agglomeration** utilizes an ion's charge to bind together fine particulate matter (e.g. PM2.5) until they precipitate out of the air. **Sterilization** occurs when ions bombard the surface of microorganisms (e.g. *E. Coli*), which rob the cell wall of hydrogen atoms, thus hindering its ability to reproduce and interact with other organisms. **Oxidation** changes the chemical composition of noxious gasses, (e.g. VOCs), neutralizing the pollutant and making it water soluble to be washed away with rain.

HYDROXYL RADICAL: OXIDATION & RESILIENCE OF ATMOSPHERIC CLEANING

Ions are the precursor to a group of aerosols, the reactive oxygen species, that oxidize VOCs and other noxious gasses in the atmopshere. Of the great variety of reactive oxygen species, none are more central to atmospheric cleaning than the Hydroxyl Radical (OH). Known as "the detergent of the atmosphere," OH molecules are the main line of defense between anthropogenic air pollution and the fragile stratospheric ozone layer. The importance of OH to overall atmospheric health is particularly impressive given it's short lifespan of less than one second.

There are two main ways atmospheric OH is created. The first and most common way is through the ionization of ozone molecules via UVB radiation (340nm).[17] The excited oxygen ion then reacts with water vapor to form a hydroxyl radical (OH). The other way OH is created is through the recycling of OH during secondary chemical reactions with hazardous aerosols like NOx.[18] This means its concentration is correlated with the concentration of the very polluting gasses it is tasked with removing. As recent models indicate, the result is an extensive redistribution of OH near polluted regions and away from the marine troposphere.[18]

This chemical recycling process describes another of nature's most powerful resilience fundamentals: the negative feedback loop. Scientists for years worried about the health of this atmospheric cleaning process given the unprecedented anthropogenic pollutant loads. However, recent analysis has indicated not only does hydroxyl radical concentration persist despite higher noxious gasses, it is actually sustained by those noxious gasses.[19] As a concept to emulate in human systems, few mechanisms rival the ingenuity of the negative feedback loop.

OH BREAKS DOWN:

VOCs	$\bullet OH + RH = H_2O + R\bullet$
NOx	$\bullet OH + NO_2 = HNO_3$
CO	$\bullet OH + CO = CO_2 + H$
CH_4	$\bullet OH + CH_4 = CH_3\bullet + H_2O$

$\bullet$ = Unpaired Electron

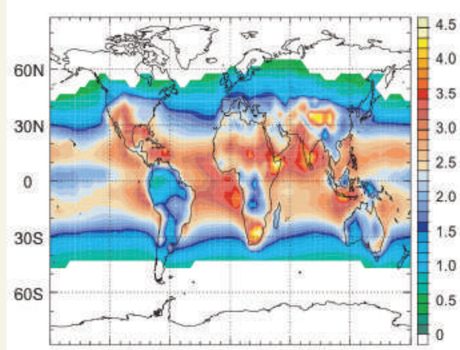
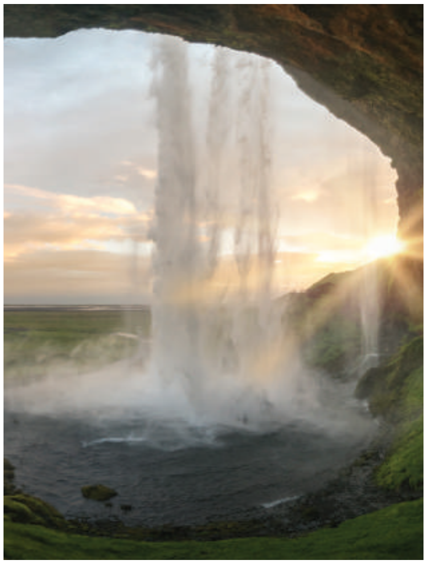


Figure: *Annual mean OH concentrations near the earth's surface.*

Graphic Credit: Lelieveld et al., 2004



THE LENARD EFFECT

Water shearing, also known as the 'Lenard Effect', *is the dominant mechanism by which air surrounding a waterfall achieves exceptionally high ion concention—often in excess of 5,000 ions/cm³.*[24,25,26] *As water droplets bump into each other they create a polarized spray of water droplets, which then interact with air molecules to form superoxides (O_2^-).*[20,32] *Those superoxides quickly combine with water molecules to form a more stable ion ($O_2^-(H_2O)_n$).*[20,32]

Image Credit: Joshua Sortino / Unsplash

Ions are created naturally when various energy sources interact with air molecules, including cosmic radiation, corona discharge from lighting, water shearing (e.g. waterfall or showers), nuclear radiation from radioactive rock strata, and even plants.[20] Ion concentration varies depending on proximity to energy sources and ion sinks. Ambient air ion concentration for unpolluted air typically falls between 300–1,000 ions/cm³.[21,22,23] Whereas, unique environmental conditions contribute to ion concentration in excess of 5,000 ions/cm³ near waterfalls and high mountains.[24,25,26] Some attribute our perception of clear air near waterfalls and high elevations to this phenomenon. However, it should be noted that there is no proven mechanism for humans to perceive ions, nor is there a proven physiological response to air ions.

Indoors, particularly in urban and suburban locations, air ion concentration drops significantly. This is partly due to indoor air pollutants that deplete air ions as well as a strong electric field produced by common interior materials made of plastics and metals such as computer screens, carpet, and HVAC ducts. Typical concentration of urban indoor air ions falls between 200–500 ions/cm³.[27] In one study of Los Angeles International Airport (LAX) air ion concentration was measured to be as low as 75 ions/cm³ in some areas.[28] Because of the utility of air ions, areas of low-ion concentration are susceptible to longer-persisting airborne pollutants and a greater likelihood that a virus will spread from one individuals to another. Having since addressed air quality issues with air ionization treatment, LAX air ion concentration rose to 824 ions/cm³, a value more in line with unpolluted outdoor environments.[28]

APPLYING ATMOSPHERIC PROCESSES TO IAQ MANAGEMENT

Conceptually, insights from atmospheric cleaning could help move indoor ventilation strategies away from the "cradle to grave" framework toward a more circular one. In comparison to a single-pass air ventilation strategy, the use of air-cleaning molecules to manage pollutants allows buildings to recirculate air that has already been temperature- and humidity-conditioned. The result is improved IAQ *and* lower energy consumption. Such a strategy partially decouples indoor air quality from the amount of outdoor air introduced, so the ventilation system is tasked solely with achieving the desired indoor CO_2 levels. Carbon dioxide can be an important determinant of cognitive performance indoors.[10]

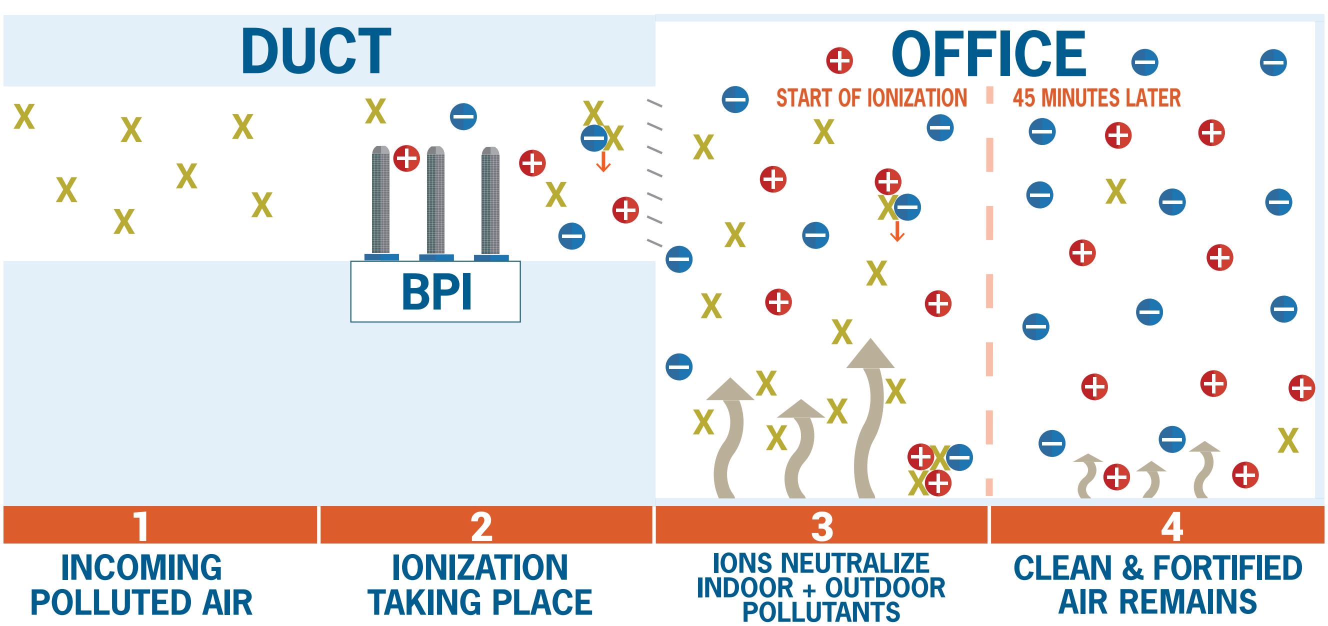
A key challenge to addressing human design challenges with bio-inspired innovation is in recognizing the differences between natural and man-made environments. For instance, IAQ management is limited by centralized sources of conditioned air and of the energy required to create air cleaning molecules. One emerging technology, known as photocatalytic oxidation (PCO), introduces oxidizing aerosols—most often the hydroxyl radical (see sidebar)—into indoor air to remove VOCs and microorganisms. While such a mechanism is highly effective in Earth's atmosphere, where free radicals can be created homogeneously throughout the stratosphere, a centralized source of hydroxyl radicals indoors cannot travel very far with a lifespan of less than one second. As a result, PCO works much like UV light sterilization, cleaning air when it passes through the duct.

Bi-polar ionization (BPI), another technology mirroring the mechanisms for atmospheric self-cleaning, moves one step beyond PCO by enabling air cleaning to occur through a space. BPI introduces positive and negatively charged ions into the air to neutralize VOCs, PM, bacteria, viruses, mold and odors. Because of the longer lifespan of air ions—typically 5 to 60 seconds—they can travel farther and remain active for longer. These air ions essentially fortify office air against air pollutants that emanate from indoor and outdoor sources alike, as opposed to only those that pass through a duct.

HOW BI-POLAR IONIZATION WORKS

The diagram below shows air traveling through a duct into an office space. Bi-polar ionization emits positive and negative ions within the duct that move into office space to neutralize air pollutants eminating from outdoor and indoor sources.

Image Credit: Terrapin Bright Green



EFFECT OF AIR IONS ON BACTERIA

The two petri dishes illustrate the sterilization effects of air ionization on a chamber aerosolised with Salmonella enteritidis*. The left sample is untreated; the right is treated with negative air ions. Photo taken in a lab operated by the United States Department of Agriculture.*

Image Credit: Ken Hammond, USDA

One company that has adopted the bi-polar ionization strategy is AtmosAir Solutions. Their system restores indoor ion concentration to levels (ions/cm^3) found in nature. In the same way tropospheric ions help to clean the air we breathe outdoors, the bi-polar ionization system delivers ionized oxygen molecules that neutralize VOCs, sterilize pathogens, and agglomerate fine particulate matter indoors. Unlike atmospheric ionization, bi-polar ionization does not produce ozone as a by-product.

Recent third-party laboratory and field testing has demonstrated the effectiveness of bi-polar ionization, exhibiting an 85.8% dust particle decay rate as compared to 12.8% natural decay rate without the system.[29] Lab tests conducted by Syracuse University's Building Energy and Environmental Systems Laboratory revealed reductions of over 90% for all of the most common indoor VOCs tested.[30] When testing against three bioaerosolized microorganisms, the bi-polar ionization system reduced prevalence by 99.98%.[31]

Furthermore, because of the *nature* of BPI technology, air quality improvements do not come at the expense of building energy use. In fact, quite the opposite is true. BPI allows building systems to reduce outside air intake by up to 50%. Assuming low enough CO_2 levels can be maintained (550-950ppm), this can translate into an HVAC energy reduction of around 20%.[10]

CONCLUSION

With inspiration from the atmospheric processes that support liveability on Earth, bi-polar ionization technology purifies and fortifies indoor air. It supports a progression in indoor environmental quality management toward decoupling outdoor air intake and IAQ management. And most importantly, it supports a workplace environment conducive to high performance and productivity.

Numerous buildings typologies—from single-family homes to health care facilities—could benefit from bi-polar ionization whether to address existing air quality issues or to lower energy use. The technology allows engineers to rethink HVAC management strategies and companies to rest assured they are caring for their employees and their bottom line. □

ENDNOTES

A. The average adult at rest takes between 12–20 breaths per minute.[2] Given 16 breaths per minute, and an average respiratory tidal volume (air volume inhaled each breath) of 500mL, this equates to 8 liters per minute, or 11,520 liters per day.[3]

B. BOMA International (2017) found average office rent to be $21.98/sqft and office operational expenses to be $8.07/sqft.[13] To determine employee compensation per square foot per year, the average total compensation (salary and benefits) for an employee in the Professional and Business Services sector ($85,925) was divided into expected average space per worker (151sqft by 2017) to get $569.04/sqft.[12,14] Employee costs ($569.04/sqft) is therefore 18.9 times more expensive per square foot than rent and energy costs combined ($30.05/sqft).

C. The average total compensation (salary and benefits) for an employee in the Professional and Business Services sector is $85,925.[12] Given an office with 100 employees, the average annual employee salaries and benefits would amount to $8,592,500. Wargocki, Wyon, and Fanger (2000) saw, on average, a 1.9% increase in office task performance for every two-fold increase in air quality.[11] Given two offices with a discrepancy of four-fold in air quality, employees would perform 3.8% better in the improved IAQ office. This difference translates into approximately $326,496 squandered as unproductive time in the office with poor IAQ.

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