Buildings, Indoor Environment, and Human Health and Performance

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Date: 30 April 2021

Buildings, Indoor Environment, and Human Health and Performance

A dissertation presented

by

Emily Jones

to

The Department of Population Health Sciences

in the Environmental Health Field of Study

in partial fulfillment of the requirements

for the degree of

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Buildings, Indoor Environment, and Human Health and Performance

ABSTRACT

Indoor environmental quality in office buildings can impact the health and performance of office workers. Characterizing these impacts and evaluating solutions for reducing harmful exposures are important in order to protect office workers from negative health outcomes and from reduced productivity. The aim of this dissertation was to evaluate the impacts of building operations on indoor environmental quality and how indoor exposures impact health and work performance, with a focus on three specific indoor environmental quality parameters.

First, we characterized indoor fine particulate matter ($PM_{2.5}$) levels in 37 office buildings in China, India, the United Kingdom, and the United States and used statistical models to evaluate associations between building filter efficiency and indoor $PM_{2.5}$ concentrations during work hours and non-work hours. We found that indoor $PM_{2.5}$ sometimes exceeded health-based outdoor exposure guidelines during work hours in China and India and that buildings with filters with higher efficiencies tended to have lower indoor $PM_{2.5}$ levels. Second, we evaluated associations between building features and indoor relative humidity (RH) levels in 43 office buildings in China, India, Mexico, Thailand, the United Kingdom, and the United States. We also evaluated associations between building RH levels and occupant-reported symptoms. RH was more commonly low (<40% RH) than high (>60% RH) and RH levels tended to be lower in less tropical regions, in winter months, when outdoor RH or temperature was low, and late in the workday. For RH levels between 14% and 70%, we also found gender-specific linear associations between RH and several occupant-reported symptoms, with higher adjusted odds of reporting three symptoms among females (dry or itchy skin and two mucous membrane symptoms) and two symptoms among males (dry or itchy skin and unusual tiredness, fatigue or drowsiness) occurring at lower RH levels. Third, we evaluated associations between temperature and outcomes of creativity and intuitive judgement in 78 young adults in a laboratory environment. We found that increasing temperatures across the range of 65.5-78.6 F were consistently associated with higher scores on tests of divergent and convergent creativity among males and females. We also found that females tended to be uncomfortable in slightly cool temperatures and that females who reported being thermally uncomfortable had lower scores on a test of divergent creativity compared to females who were thermally comfortable.

In summary, we found that building design and operations can impact indoor environmental quality in ways that affect building occupants' health and work performance. Our work also points to solutions that can be implemented in office buildings to reduce exposures that harm health and performance.

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In memory of my father, Tom Gilson. With love.

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ABBREVIATIONS

AB5C: Abridged Big Five-Dimensional Circumplex

AER: air exchange rate

ASHRAE: American Society of Heating, Refrigerating and Air-Conditioning Engineers

Aug: August

AUT: alternative uses test

BASE: Building Assessment Survey and Evaluation

C: degrees Celsius

CDDs: cooling degree days

cfm: cubic feet per minute

CI: confidence interval

CNS: central nervous systems

CO_2: carbon dioxide

cRAT: compound remote associates test

dBA: decibels A

Dec: December

F: degrees Fahrenheit

Feb: February

gr_m/lb_{da}: grams of moisture per pound of dry air

HDDs: heating degree days

HEPA: high-efficiency particulate air

IEQ: indoor environmental quality

I/O ratios: ratios of indoor $PM_{2.5}$ to outdoor $PM_{2.5}$

IPIP: International Personality Item Pool

ISO: International Organization for Standardization

Jun: June

km: kilometers

LEED: Leadership in Energy and Environmental Design

m: meters

Mar: March

MERV: minimum efficiency reporting value

ms: milliseconds

Nov: November

OR: odds ratio

OSHA: Occupational Safety and Health Administration

$PM_{2.5}$: particulate matter with an aerodynamic diameter of 2.5 microns or less

PM_{10}: particulate matter with an aerodynamic diameter of 10 microns or less

ppm: parts per million

RH: relative humidity

SD: standard deviation

Sep: September

Temp.: temperature

$\mu g/m^3$: micrograms per meters cubed

μm: micrometers

UK: United Kingdom

ULPA: ultra low particulate air

USA: United States

USEPA: United States Environmental Protection Agency

w/: with

WHO: World Health Organization

w/o: without

%ile: percentile

CHAPTER 1: INTRODUCTION

Associations between IEQ and Health and Performance in Office Buildings

The health and performance of office workers can be impacted by indoor environmental quality (IEQ) in their workplaces. Acute exposures to suboptimal workplace IEQ can impact worker health and performance within a single workday. For example, a review of studies of office work reports that an increase in room temperature from 71.6 F to 86.0 F is associated with an 8.9% decline in cognitive function;[1] these effects can be present after hour of exposure.[2,3] Moreover, chronic exposures to suboptimal workplace IEQ can contribute to workers' future development of health impairments. For example, chronic exposures to particulate matter with an aerodynamic diameter of 2.5 microns or less ($PM_{2.5}$) have long been known to have detrimental effects on cardiovascular and respiratory health.[4–7] These effects may occur after long latency, but the potential for such effects as a result of workplace exposure exists, particularly because employed adults spend a substantial amount (approximately 19-25%[8]) of their time working. Health and performance effects from acute and chronic exposures to a variety of poorly-controlled IEQ parameters, including temperature, indoor $PM_{2.5}$, and relative humidity (RH), can be seen at levels of these parameters that are commonly present in office settings. Good IEQ in office buildings can support worker health and performance during work hours and protect workers against the future development of health impairments as a result of chronic workplace exposures.

A Brief History of IEQ in Office Buildings

Historically, the fields of occupational health and environmental health have focused less attention on office work compared to more fundamentally hazardous occupations like mining and manufacturing.[9,10] Since its establishment in 1970, the United States Occupational Safety and Health Administration (OSHA) has focused on establishing enforceable exposure limits for toxic substances, including carcinogens, and on reducing conditions that may lead to injury or death.[11] Most businesses performing office work in the United States fall within OSHA's purview.[12] However, OSHA does not have a general IEQ standard, although some of its standards and interpretations may be relevant for certain situations relating to building IEQ.[13]

In the early 1970s, around the time when OSHA was established, office worker health concerns became more prominent after a push for lower ventilation rates to improve office building energy efficiency resulted in tighter buildings where indoor air pollutants accumulated and triggered and uptick in reports of building-related symptoms including headache, respiratory irritation, fatigue, and rash.[14] The term "sick building syndrome" was coined to describe this phenomenon of illness caused by inadequate ventilation or the presence of air contaminants in non-industrial spaces.[14] Since the initial reports of sick building syndrome, research in office buildings and IEQ research more generally have accelerated. Calls for coordinated investigations into potential health effects of indoor air pollutants and for thoughtful evaluations of interventions to protect public health indoors[15,16] led to the groundbreaking United States Environmental Protection Agency's (USEPA's) Building Assessment Survey and Evaluation (BASE) Study in 1994-1998.[17] This study assessed determinants of indoor air quality in 100 office buildings in the United States and the data collected as part of this effort are still used today as benchmarks for indoor air quality and occupant perceptions in office buildings. In the decades following the USEPA's BASE Study, researchers worked to understand how behaviors and time-activity patterns influenced indoor exposures and developed improved estimates of personal exposures to certain indoor pollutants in workplaces, homes, and other indoor environments.[18–21] In parallel with the expansion of indoor exposure assessment, the development of more sophisticated measures of worker health and performance paved the way for more advanced studies in offices, including the Harvard CogFx Studies that evaluated associations between several IEQ parameters and cognitive function scores.[22,23]

Today, office building design and operations are guided by standards published by professional organizations, such as the International Organization for Standardization (ISO) and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). For example, ANSI/ASHRAE Standard 62.1-2019: Ventilation for Acceptable Indoor Air Quality,[24] published in its original form in 1973,[25] discusses ventilation requirements for different kinds of spaces and indicates when air filtration should be added. ANSI/ASHRAE Standard 52.2-2017: Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size[26] establishes methods for testing and rating air filters based on their particle removal efficiency. ANSI/ASHRAE Standard 55-2020: Thermal Environmental Conditions for Human Occupancy,[3] published in its original form in 1974,[25] explains how thermally adequate conditions can be maintained in occupied buildings. While these guidelines provide good baseline targets for building operation, their goal is adequate, comfortable IEQ rather than optimal, health-promoting IEQ and they are limited to some extent by the current state of IEQ research and by the challenge of co-optimizing comfort, health (e.g. reducing disease spread), odor control, and/or energy efficiency.[25] As a result, following these standards will not necessarily fully optimize the health and work performance of building occupants and additional research is needed to further understand what optimal building conditions are and how best to achieve them.

Gaps in Research Regarding Optimizing IEQ for Health and Performance

In order to optimize buildings for health and performance, additional research is necessary to address several important gaps. First, a majority of in situ IEQ research focuses on a single building or a small subset of buildings in close proximity to each other. IEQ should also be characterized in a diverse array of operating, occupied buildings across the globe, as local practices and climate can influence IEQ. Second, a majority of IEQ research relies on measurements collected over a relatively short timeframe, such as days or weeks. IEQ should also be characterized across a full year of data to account for seasonal cycles in local practices or climate that could influence IEQ. Third, research on the influence of IEQ on building occupants' health or performance in situ often relies on exposures or outcomes collected over timeframes that do not truly represent the timeframes over which the exposure would be expected to impact the outcome. For example, one analysis of 95 office buildings from the USEPA's BASE Study evaluated associations between indoor RH and temperature measurements from a nine-hour workday and symptoms reported over the four preceding weeks;[27] to reduce potential sources of bias, acute impacts of RH or temperature should be investigated by comparing RH or temperature levels measured over a short period (e.g. hours) with subsequent symptoms. Associations between IEQ and health or performance outcomes should be evaluated using data collected over appropriate timeframes to avoid certain biases like recall bias and to arrive at more precise estimates of the effect of IEQ exposures on health outcomes. Finally, assessments of the influence of IEQ on building occupants' performance has traditionally focused on a narrow definition of performance focused on attention, memory, reasoning and processing speed.[1,28,29] The impact of IEQ on additional cognitive processes, like creativity and intuition, should also be evaluated as these processes are important in the workplace.[30–32]

Dissertation Research Framework

This dissertation is comprised of three studies and focuses on how three IEQ parameters – $PM_{2.5}$, RH, and temperature – impact office workers in their workplaces. By evaluating how building operations impact these parameters and how exposures to these parameters impact health and work performance (Figure 1.1), the results of this dissertation directly translate into building management strategies that support improved worker health and performance.

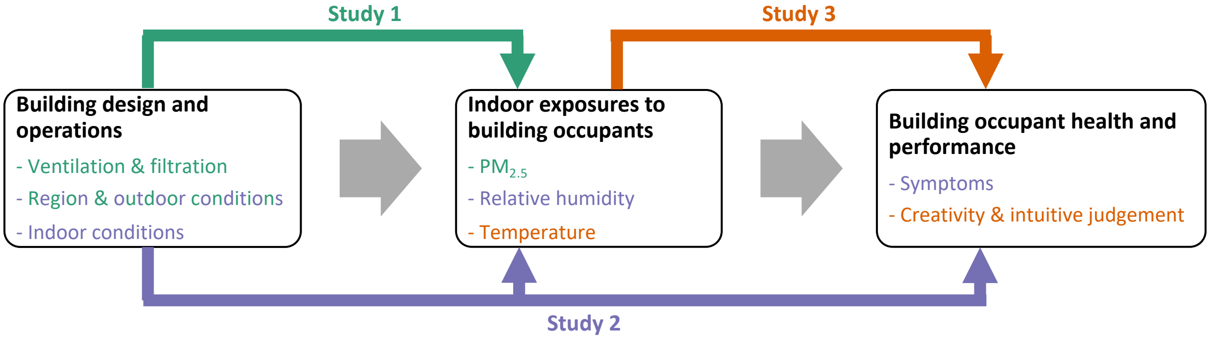

Figure 1.1: Research framework for the three studies described in this dissertation.

Study 1 (in Chapter 2) addresses workplace exposure to $PM_{2.5}$, as it investigates the role building operations and design can play in determining indoor $PM_{2.5}$ exposures at work. To date, the majority of exposure science and epidemiological research pertaining to $PM_{2.5}$ focus on outdoor $PM_{2.5}$ rather than indoor $PM_{2.5}$. This prior work has translated into standards and guidelines, such as the USEPA National Ambient Air Quality Standards, that limit daily and annual outdoor $PM_{2.5}$ levels. However, adults spend only about 10-19% of their time outdoors compared to about 81-90% indoors.[33–36] Indoor $PM_{2.5}$ concentrations may diverge from outdoor $PM_{2.5}$ concentrations depending on whether indoor $PM_{2.5}$ sources are present and on how much outdoor $PM_{2.5}$ is allowed to enter the building. Understanding how building operations affect indoor $PM_{2.5}$ concentrations is important because exposure to $PM_{2.5}$ has harmful short- and long-term effects on health. In Study 1, we measured indoor $PM_{2.5}$ for one year in multiple locations inside 37 office buildings with mechanical or mixed-mode ventilation located in China, India, the United Kingdom, and the United States. Using statistical models, we evaluated associations between filter efficiency and $PM_{2.5}$ during work hours and non-work hours. Our results indicate that high-efficiency air filtration in office buildings can be used as a public health tool to reduce exposure to indoor $PM_{2.5}$.

Study 2 (in Chapter 3) addresses workplace exposures to RH, as it investigates how building operations impact indoor RH and how indoor RH impacts occupant health. RH that is too low or too high can enhance viral transmission[37–43] or promote mold growth.[44,45] Furthermore, although it has been demonstrated that RH can affect occupant health and comfort,[46–50] questions remain about the shape of this association as well as whether findings from studies of mixed gender populations in northern latitudes also apply to males or females in other climates. In Study 2, we addressed these gaps using one year of RH measurements from office buildings in countries around the world. First, we characterized RH in 43 office buildings in China, India, Mexico, Thailand, the United Kingdom, and the United States and looked at what building characteristics or local factors were associated with indoor RH levels. We also evaluated associations between indoor RH and seven individual symptoms reported over the course of one year by 227 male and female office workers in India, the United Kingdom, and the United States. Our results indicate that RH was linearly associated with the odds of reporting specific symptoms, including two mucous membrane symptoms among females, and that interventions to increase RH in office buildings may be useful to reduce symptom reports and other known issues including viral transmission.

Study 3 (in Chapter 4) addresses workplace temperature and its effects on occupant creativity and intuitive judgment. Historically, there has been a substantial amount of research on the effects of IEQ in general, and temperature in particular, on work performance. However, the various tests of work performance that have been favored measure cognitive processes like attention, memory, reasoning, and processing speed.[51–59] While these skills are undoubtedly valuable for work performance, creativity and intuitive judgement are also increasingly important for office workers' productivity and decision making across many occupations.[30–32] In Study 3, we addressed these gaps by exposing 78 young adults to temperatures between 65.5 F and 78.6 F for at least 54 minutes before asking them to complete tests of two domains of creativity and of intuitive judgement. We then evaluated associations of both temperature and self-reported thermal comfort with performance on the creativity and intuitive judgement tests. Our results indicate that warmer temperatures over the exposure range in the study promoted both types of creativity among males and females and that females, who reported more discomfort in cooler temperatures, performed better on all four domains of divergent creativity when they were thermally comfortable. Controlling indoor environmental conditions to be thermally comfortable for males and females is expected to result in better creativity among office workers.

Overall, this dissertation hopes to advance our understanding of how IEQ can impact the health and work performance of office workers, as well as how health-protective and performance-optimizing IEQ conditions can be achieved.

CHAPTER 2: THE EFFECTS OF VENTILATION AND FILTRATION ON INDOOR $PM_{2.5}$ IN OFFICE BUILDINGS IN FOUR COUNTRIES

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E.R.J conceptualized this analysis, contributed to carrying out the study activities, developed the statistical models, performed the formal analysis, and prepared the manuscript. J.G.C.L., A.S.Y., and P.M. contributed to carrying out the study activities and provided critical revision of the manuscript. B.A.C. and J.D.S. provided critical revision of the manuscript. J.G.A. conceptualized this analysis, acquired financial support for this project, provided critical review of the manuscript, and supervised the project.

Abstract

Fine particulate matter ($PM_{2.5}$) is an airborne pollutant associated with negative acute and chronic human health outcomes. Although the majority of $PM_{2.5}$ research has focused on outdoor exposures, people spend the majority of their time indoors, where $PM_{2.5}$ of outdoor origin can penetrate. In this work, we measured indoor $PM_{2.5}$ continuously for one year in 37 urban commercial offices with mechanical or mixed-mode ventilation in China, India, the United Kingdom, and the United States. We found that indoor $PM_{2.5}$ concentrations were generally higher when and where outdoor $PM_{2.5}$ was elevated. In India and China, mean workday indoor $PM_{2.5}$ levels exceeded the World Health Organization's 24-hour exposure guideline of 25 μg/m^3 about 17% and 27% of the time, respectively. Our statistical models found evidence that the operation of mechanical ventilation systems could mitigate the intrusion of outdoor $PM_{2.5}$: during standard work hours, a 10 μg/m^3 increase in outdoor $PM_{2.5}$ was associated with 19.9% increase in the expected concentration of indoor $PM_{2.5}$ ($p<0.0001$), compared to a larger 23.4% increase during non-work hours ($p<0.0001$). Finally, our models found that using filters with ratings of MERV 13-14 or MERV 15+ was associated with a 30.9% (95% confidence interval [CI]: -55.0%, +6.2%) or 39.4% (95% CI: -62.0%, -3.4%) reduction of indoor $PM_{2.5}$, respectively, compared to filters with lower MERV 7-12 ratings. Our results demonstrate the potential efficacy of mechanical ventilation with efficient filtration as a public health strategy to protect workers from $PM_{2.5}$ exposure, particularly where outdoor levels of $PM_{2.5}$ are elevated.

Introduction

Particulate matter with an aerodynamic diameter less than 2.5 μm ($PM_{2.5}$) is an air pollutant that has been shown to have harmful acute and chronic effects on human health.

Chronic $PM_{2.5}$ exposure negatively impacts the respiratory,[4] cardiovascular,[5] and nervous systems,[60] and is associated with increased mortality rates.[7] Short-term $PM_{2.5}$ exposure, such as same-day outdoor $PM_{2.5}$, is also associated with hospital admissions for respiratory and cardiovascular diseases[61] and with increased mortality even at concentrations below the World Health Organization's (WHO's) 24-hour exposure guideline of 25 $\mu g/m^3$.[62,63] $PM_{2.5}$ may even have acute effects on cognitive function; increases in outdoor 12-hour $PM_{2.5}$ over the range from 5 $\mu g/m^3$ to 40 $\mu g/m^3$ have been associated with an increase in errors in skilled task performance.[64]

Although much of our knowledge about the health effects of $PM_{2.5}$ has come from epidemiological studies of outdoor $PM_{2.5}$ exposures, exposures to $PM_{2.5}$ (from both indoor and outdoor sources) that occur indoors may have a larger impact on people's health than outdoor exposures because adults spend the majority of their time, in general between 82% and 90%, inside buildings.[34–36] The indoor locations where people spend the most time include homes and, for employed adults, workplaces.[34,35] Employed adults in China, India, the United Kingdom (UK), and the United States (USA) worked, on average, for 25%, 24%, 19%, and 20% of the hours in 2017.[8] While indoor $PM_{2.5}$ sources, like cooking, may be significant in the home[65] and some indoor sources, like frequently-used printers, may contribute to $PM_{2.5}$ in offices,[66] $PM_{2.5}$ of outdoor origin is likely more important in workplaces like office buildings where major indoor sources are less common, particularly in places with high outdoor $PM_{2.5}$ concentrations.

The degree of outdoor $PM_{2.5}$ penetration into a building depends on the building's design and operations. Air filters in building ventilation systems can remove $PM_{2.5}$ from outdoor air before it is distributed to occupied spaces. In the USA, air filters are rated using minimum efficiency reporting value (MERV) ratings that range from 1 (lowest efficiency) to 16 (highest efficiency) as defined by ANSI/ASHRAE Standard 52.2-2017.[26] The MERV rating system is similar to a new global standard from the International Organization for Standardization (ISO), ISO 16980, which replaced an older European Standard called EN 779 in July 2018.[67] Filters with MERV 8 ratings are considered standard in office buildings where filtration is present, as these filters are recommended by the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) for outdoor air being distributed to occupied spaces in areas where the PM_{10} national standard for outdoor air is exceeded.[24] MERV 8 filters are designed to have an average particle removal efficiency of at least 20% for particles between 1.0 and 3.0 μm, while more efficient MERV 13 filters are designed to have an average particle removal efficiency of at least 85% for the same particle size range.[26] In practice, filter performance varies due to differences in how the filters are installed, how often the filters are replaced, how polluted the air being filtered is, and how well the systems are maintained. An experiment in an office building in Philadelphia, Pennsylvania found that the $PM_{2.5}$ removal efficiency of MERV 8 filters ranged from approximately 2% to 39% with a median of 17%, while the $PM_{2.5}$ removal efficiency of MERV 14 filters ranged from approximately 62% to 90% with a median of 72%.[68]

In addition to the level of filtration of outdoor air, the route and amount of outdoor air entering a building can influence the degree of outdoor $PM_{2.5}$ penetration into buildings. Higher indoor $PM_{2.5}$ levels can result from higher ventilation air exchange rates (AERs) that bring more outdoor air indoors instead of recirculating air within a building, particularly when filters with ratings of MERV 8 or lower are used.[68,69] However, it has been demonstrated that increasing the filter rating from MERV 8 to MERV 14 or 15 can more than compensate for increased indoor $PM_{2.5}$ concentrations that can result from increasing the outdoor air ventilation rate from 1.0 hour^{-1} to 5.4 hours^{-1},[68] indicating that filtration may be an effective way to control the penetration of outdoor $PM_{2.5}$ in buildings where high AERs are used to protect occupant health, comfort, and productivity.[70–72] Higher indoor $PM_{2.5}$ levels can also result from infiltration of outdoor $PM_{2.5}$ through the building envelope, which may occur when ventilation systems that normally maintain positive pressure in buildings during occupied hours are instead operating at reduced capacity during non-work hours.[69] Limiting infiltration of outdoor air into a building, as well as using filters to protect against the introduction of outdoor $PM_{2.5}$ by high outdoor air ventilation rates, may be able to reduce the degree of indoor exposure to $PM_{2.5}$ of outdoor origin while promoting optimal indoor air quality.

Less is known regarding how ventilation and filtration impact real-world indoor $PM_{2.5}$ exposures across different countries under normal building operating conditions, despite some evidence from experimental work. One study that measured indoor $PM_{2.5}$ levels in operating buildings is exceptional for its size and scale: the United States Environmental Protection Agency's Building Assessment Survey and Evaluation (BASE) study, which was carried out in 1994-1998.[73] This landmark study investigated indoor environmental parameters, ventilation characteristics, and occupant symptoms in 100 non-problem office buildings in the USA and found that integrated 8- to 10-hour indoor building $PM_{2.5}$ concentrations ranged from 1.3 $\mu g/m^3$ to 24.8 $\mu g/m^3$ (measured in a single location in 70 of the 100 buildings and as the average of three locations in the remaining 30 buildings).[73] However, the one-time, largely single-location-per-building sampling strategy of the BASE study, and of most of the other studies investigating indoor $PM_{2.5}$, does not account for spatial variability of $PM_{2.5}$ within buildings or for variability over the course of a day, over seasons, or under different ventilation scenarios. Moreover, most studies investigating indoor $PM_{2.5}$ are unable to explore variation between buildings or regions because of small sample sizes. Even the BASE study, which included 100 buildings, did not explore whether ventilation operations and filtration were responsible for the variation in indoor $PM_{2.5}$ levels that was observed among different buildings.[73]

To determine how ventilation operating schedule and filtration efficiency influence $PM_{2.5}$ levels in operating and occupied office buildings, we conducted a multi-country, one-year longitudinal study of real-time indoor $PM_{2.5}$ levels at multiple workstations within each of 37 office buildings located in China, India, the UK, and the USA. Compared to prior work, our work is innovative in its geographic scope, long duration, high temporal resolution, and use of statistical models rather than descriptive statistics to evaluate associations between filtration efficiency and indoor $PM_{2.5}$.

Materials & Methods

Study Design

The Global CogFx Study is a year-long observational study of 43 office buildings in China, India, Mexico, Thailand, the UK, and the USA. The buildings in the Global CogFx Study represent a convenience sample of urban commercial office spaces. In each building, study activities were undertaken by individuals working at a single company and these companies, in many cases, occupied just a portion of their larger buildings (e.g. company leased one floor in large, multi-tenant building). In some cases, multiple office locations of a single company participated in the study. The participating companies included architecture firms, software companies, real estate companies, and engineering firms, as well as eight companies in green buildings in China from a previous study.[74] All participating companies were required to have at least ten employees working in the office building at least three days a week. At each participating company, individual employees were recruited to participate in the study. Each individual participant completed study questionaries and tests on a custom smartphone app, wore a wristband activity tracker, and hosted an environmental sensor package at or near their workstation for their building's one year of participation. The study protocol was reviewed and approved by the Institutional Review Board at the Harvard T.H. Chan School of Public Health.

Study Population

This analysis used data from a subset of the 43 buildings that participated in the Global CogFx Study. For this analysis, we included only the four countries with at least two buildings participating and only the buildings where $PM_{2.5}$ measurements were collected for at least some part of the study period. These criteria resulted in the exclusion of Mexico and Thailand, since each of these countries only had one participating building, and of one building in the USA, because the environmental sensor packages used in this building for the duration of the study did not measure $PM_{2.5}$, leaving a total of 40 buildings in four countries. Of these 40 buildings, one building (in India) was excluded because it was the only building that reported using natural ventilation, which is expected to result in different indoor $PM_{2.5}$ dynamics than mechanical ventilation, and an additional two buildings (in India) were excluded because we were unable to obtain information about their air filters. These exclusions left 37 buildings in the final analysis: eight buildings in China (three in Chengdu, three in Shanghai, and two in Zhuhai), seven buildings in India (three in Bengaluru and one each in Chennai, Gurugram, Hyderabad, and Mumbai), six buildings in the UK (two in Croydon and one each in Birmingham, Cambridge, London, and Sheffield), and sixteen buildings in the USA (two in Los Angeles, two in San Francisco, and one each in Boston, Clearwater, Chicago, Cleveland, Denver, Minneapolis, New York City, Omaha, Overland Park, Phoenix, Seattle, and Washington DC). Each building participated in the study for a full year, with participation in each country occurring over the following time periods: 5/29/2018 – 8/3/2019 in China, 11/13/2018 – 11/13/2019 in India, 7/1/2018 – 7/25/2019 in the UK, and 10/1/2018 – 3/20/2020 in the USA.

Building Assessment

Information about building design and operational practices was acquired through an online questionnaire or by email correspondence with an individual building contact from the participating company in each building. For this analysis, important questions from the building questionnaire included questions about ventilation type and level of filtration. All building contacts indicated whether their building used natural ventilation, mechanical ventilation, or a combination of the two (i.e. mixed-mode ventilation). They also indicated whether their building ventilation system used filters and, if so, what filter efficiency rating was used. Filter efficiency ratings were reported as MERV ratings; in cases where other rating types were reported, ratings were converted to MERV ratings. Building contacts also answered questions about green certifications, healthy building certifications, building occupancy, building age, and other building operations and design parameters.

Indoor Environmental Assessment

Within the office space of each participating company included in this analysis, between one and 12 (median five) low-cost environmental sensor packages were set up on or near workers' desks to measure $PM_{2.5}$, temperature, relative humidity, and carbon dioxide (CO_2) at one- to ten-minute intervals. Five different low-cost sensor packages were used in the 37 buildings in this analysis, including the Harvard Healthy Buildings Sensor (a custom sensor package built for the Global CogFx Study at the Harvard T.H. Chan School of Public Health), the Tsinghua IBEM Sensor (a custom sensor package built at Tsinghua University[74]), the Awair Omni (Awair, Inc., San Francisco, USA), the ChemiSense CS-001 Indoor Air Quality Monitor (ChemiSense Inc., Berkeley, USA), and the Tongdy MSD-16 Sensor (Tongdy Sensing Technology Corporation, Beijing, China). Both of the custom sensor packages, the Harvard Healthy Buildings Sensor and the Tsinghua IBEM Sensor, contained Plantower PMS3003 devices (Beijing Plantower Co., Ltd, Beijing, China) to measure $PM_{2.5}$ concentrations. According to manufacturers' specifications and external evaluations of the five environmental sensor packages, they all use laser-based methods to estimate $PM_{2.5}$ concentrations (see Table 2.1 for further details of $PM_{2.5}$ sensor specifications). Of the buildings included in this analysis, the buildings in China used the Harvard Healthy Buildings Sensor and/or the Tsinghua IBEM Sensor; the buildings in India used the Harvard Healthy Buildings Sensor or the Awair Omni; the buildings in the UK used the Harvard Healthy Buildings Sensor and the Awair Omni; and the buildings in the USA used the Harvard Healthy Buildings Sensor, the Awair Omni, the ChemiSense CS-001 Indoor Air Quality Monitor, or the Tongdy MSD-16 Sensor.

Table 2.1: PM$_{2.5}$ sensor specifications for environmental sensor packages used in buildings from the Global CogFx Study included in this analysis.

Package Name	**PM$_{2.5}$ Sensor Name**	**Type of PM$_{2.5}$ Sensor**	**Range (μg/m^3)**	**Smallest Particle Diameter**	**Sensor Output Resolution**	**Accuracy**	**Third Party Evaluation**
Harvard Healthy Buildings	Plantower PMS3003[a]	Laser light scatter[b]	NR	0.3 μm [b]	NR	0 - 100 μg/m^3: ±10 μg/m^3 100 - 500 μg/m^3: ±10%[c]	NR
Tsinghua IBEM	Plantower PMS3003[d]	Laser light scatter[e]	0-1000[e]	0.3 μm [b]	1 μg/m^3 [e]	20 - 500 μg/m^3: ±10%[e]	Guaranteed by China National Institute of Metrology for PM2.5 Standard GSH/J2011 -1[e]
Awair Omni	Honeywell HPMA 115S0[f]	Laser light scatter[g]	0-1000[g]	NR	1 μg/m^3 [g]	0 - 100 μg/m^3: ±15 μg/m^3 100 - 1000 μg/m^3: 15%[g,h]	Interior RESET Air Accredited Grade B monitor[i]
ChemiSense CS-001	Sharp GP2Y-10##[j]	Laser particle counter[k]	0-500[k]	NR	1 μg/m^3 [k]	0 - 150 μg/m^3: ±5 μg/m^3 or 15% 150 - 500 μg/m^3: ±5 μg/m^3 or 20%[k]	Interior RESET Air Accredited Grade B monitor[i]
Tongdy MSD-16	NR	Laser light scatter[l]	0-1000[m]	NR	0.1 μg/m^3 [m]	10%[m]	Interior RESET Air Accredited Grade B monitor[i]

NR: Not reported

[a] Harvard Healthy Buildings sensors were constructed by the authors and their colleagues using Plantower PMS3003 sensors.

[b] PMS3003 Specification Sheet: “Laser dust sensor: PM1.0 PM2.5 PM10” by GuangZhou LOGOELE Electronic Technology Co., Ltd.

[c] Zheng et al. 2018[75]

[d] Tsinghua IBEM sensors are presumed to use Plantower PMS3003 based on observation of deconstructed sensors.

[e] Geng et al. 2019[74]

[f] Awair Omni sensors are presumed to use Honeywell HPMA 115S0 sensors based on observation of deconstructed sensors.

[g] RESET^{TM} Specification Sheet for AWAIR Omni Indoor Air Quality Monitor.

[h] Honeywell HPM Series Particulate Matter Sensors Datasheet. 32322550 Issue F.

[i] RESET Accredited Monitors webpage (https://www.reset.build/monitors).

[j] Nore 2016[76] referred to the PM$_{2.5}$ sensor as the “Sharp Compact Optical Dust Sensor” which was assumed to be one of the Sharp GP2Y-10## models (e.g. Sharp GP2Y-1010, Sharp GP2Y-1012, etc.) based on the descriptions of these products on the SHARP website (https://www.sharpsde.com/products/optoelectronic-components/sensors/air-sensors).

[k] RESET^{TM} Air Accredited Monitor Testing Report for ChemiSense CS-001.

[l] RESET^{TM} Specification Sheet for Tongdy MSD-16 Indoor Air Quality Monitor.

[m] MSD Sensors Specification Sheet: “MSD IAQ Detector – User Manual V.1707” by Tongdy Sensing Technology Corporation.

CO_2 concentrations measured by the environmental sensor packages (see Table A1 in Appendix A for details of the CO_2 sensor specifications) were used to estimate quarterly building AERs by applying the concentration decay test method to data from weekdays between 14:00 and 19:00 local time.[77] These afternoon and evening hours were selected to try to capture CO_2 concentration decays after people left the buildings in the evenings but before the building mechanical systems scaled back or turned off for the evening. If the buildings were more than minimally occupied or the outdoor air ventilation was not constant during these afternoon and evening hours, the estimated air exchange rates may be over- or under-estimates of the true air exchange rates. Briefly, daily AERs were estimated using the regression method for each valid concentration decay curve for all sensor packages in each building. Considerations from ASTM E741-11[77] and ASTM D6245-18[78] were used to define valid concentration decay curves; many sensor packages did not have valid concentration decay curves on any given day. Quarterly building AERs were then estimated by taking the 90th percentile of all estimated daily AERs from all sensor packages in each building for each three-month period (December – February, March – May, June – August, and September – November). The 90th percentile was selected to represent the typical quarterly AER for each building after reviewing the distributions of estimated AER values and the quality of their associated CO_2 decay curves.

Before the sensors were installed, visual comparisons of real-time data from at least one unit of each type of sensor package and data from collocated recently-calibrated reference instruments were performed. Reference instruments included a TSI DustTrak (TSI Instruments, USA) for $PM_{2.5}$ and a QTrak 7575 (TSI Instruments, USA) for CO_2. Before estimation of air exchange rates, CO_2 values lower than 400 ppm or greater than 5,000 ppm were removed. Before data analysis, raw indoor $PM_{2.5}$ measurements were inspected by eye and outlier points and measurements that exceeded 500 μg/m^3 were removed from the dataset. This data cleaning resulted in the removal of 0.08%, 4.48%, 0.17%, and 0.001% of the raw $PM_{2.5}$ measurements in China, India, the UK, and the USA, respectively.

Outdoor $PM_{2.5}$ Data

Outdoor $PM_{2.5}$ data were obtained from multiple official government sources through the OpenAQ Platform (https://openaq.org). These data were collected using government-approved methods (e.g. Federal Equivalent Methods in the USA); no outdoor $PM_{2.5}$ data were collected by low-cost $PM_{2.5}$ sensors. For each building, outdoor $PM_{2.5}$ was represented by data from the closest government monitor posted on OpenAQ that collected data at a frequency of at least one measurement per hour. For 32 of the 37 buildings in this analysis, there was an outdoor $PM_{2.5}$ monitor within 10 kilometers (km) of the building. The remaining five buildings (three in the UK and two in the USA) were located 13.2 km, 13.2 km, 16.8 km, 19.9 km, and 30.5 km from the closest outdoor $PM_{2.5}$ monitor. In cases where the closest outdoor $PM_{2.5}$ monitor had a period of missing data, data from the next closest monitor within 50 km of the building were used instead.

Data Analysis

All indoor $PM_{2.5}$ measurements from a given sensor were averaged by hour to standardize the interval between data points for indoor $PM_{2.5}$ and to match the frequency of the outdoor $PM_{2.5}$ measurements. For some periods of time at some buildings, outdoor $PM_{2.5}$ data were not available at any of the outdoor $PM_{2.5}$ monitors within 50 km of the building. Additionally, there were some periods when indoor $PM_{2.5}$ sensors failed to collect data. Since the causes of missing indoor and outdoor $PM_{2.5}$ data were likely device malfunctions or internet connectivity issues unrelated to the values of the missing data, it is reasonable to assume that the missing indoor and outdoor data were missing completely at random and that the complete case analysis described here is consequently unbiased. This analysis includes all indoor $PM_{2.5}$ data collected by $PM_{2.5}$ sensors during periods when outdoor $PM_{2.5}$ measurements were also collected by monitors within 50 km of the buildings in which the indoor measurements were made. Overall, 60% of the total study hours for the 37 buildings had both indoor and outdoor $PM_{2.5}$ measurements.

Generalized additive mixed models[79] were used to evaluate the impact of buildings' self-reported filter ratings on hourly indoor $PM_{2.5}$ levels. The primary analysis included two models: one model during standard work hours, when ventilation systems were assumed to be operating normally (weekdays between 9:00 and 17:00 local time), and one model during assumed non-work hours, when ventilation systems may have been scaled back or not operating (weekends or weekdays before 7:00 or after 19:00 local time). The modeled outcome was the natural logarithm of hourly indoor $PM_{2.5}$, with zeros substituted by half of the lowest non-zero $PM_{2.5}$ concentration measured by the same sensor. The replacement of zero values with half of the limit of detection was necessary to accommodate the natural logarithm transformation and has been shown to be minimally biased if zero values make up less than 5-10% of the data.[80] Indoor $PM_{2.5}$ was reported to be 0 $\mu g/m^3$ in 13% of the data used in these models, so the substitution with half of the limit of detection will be close to minimally biased. The models included nested random intercepts for the $PM_{2.5}$ sensor unit and for the building to account for non-independence of measurements made by a single $PM_{2.5}$ sensor package and of measurements made within the same building. The models also included a spline on local datetime to account for serial correlation in measurements.

The main covariate in the models was a categorical marker of filter efficiency with categories including MERV 7-12, MERV 13-14, and MERV 15 or greater. In cases where buildings reported multiple filter ratings, the maximum of the reported ratings was used to categorize the building, following the assumption that air being distributed to occupied spaces passed through filters with lower and higher ratings in series. Three buildings (two in China and one in the USA) reported using filters with ratings that fall in the high-efficiency particulate air (HEPA) or ultra low particulate air (ULPA) range. These filters are designed to perform better than filters with the highest MERV rating (MERV 16) and these three buildings were included in the MERV 15+ group.

Additional categorical covariates in the models included variables representing the countries where buildings were located (in the models for work and non-work hours) and quartiles of estimated quarterly building AERs (in the model for work hours only). Continuous covariates in the models included building age and hourly outdoor $PM_{2.5}$ concentrations. Dichotomous variables representing buildings' green building certification status (certified or not certified) and healthy building certification status (certified or not certified) were considered for inclusion in the models, but were ultimately excluded because their inclusion resulted in lower adjusted R^2 values for both models. A model with outdoor $PM_{2.5}$ lagged by one hour was also considered, but the model with concurrent indoor and outdoor $PM_{2.5}$ measurements was used as the final model because it had a higher adjusted R^2 than the lagged model.

Statistical significance was evaluated at a level of $\alpha = 0.05$ and suggestive evidence was evaluated at a level of $\alpha = 0.10$. All modeling was done using the R programming language version 3.5.3.

Results

Building Characteristics

The sizes, occupancies, ages, ventilation and filtration characteristics, certifications, and types of environmental sensor packages used in the 37 buildings in this analysis are shown in Table 2.2. Across the 37 buildings, 30 buildings had only mechanical ventilation and seven buildings had mixed-mode ventilation. The most popular filter efficiency category in buildings in this study was MERV 15+ in China, MERV 7-12 in India, MERV 13-14 in the UK, and both MERV 7-12 and MERV 13-14 (tied) in the USA.

Table 2.2: Descriptive information for all buildings in this analysis.

	All Countries	**China**	**India**	**USA**	**UK**
Total Buildings, n	37	8	7	16	6
Ventilation, n (% of Country Total)					
Mechanical Ventilation	30 (81%)	5 (63%)	5 (71%)	14 (88%)	6 (100%)
Mixed-Mode Ventilation	7 (19%)	3 (38%)	2 (29%)	2 (13%)	0 (0%)
Filter Efficiency Rating, n (% of Country Total)					
MERV 7-12	15 (41%)	3 (38%)	4 (57%)	7 (44%)	1 (17%)
MERV 13-14	14 (38%)	1 (13%)	2 (29%)	7 (44%)	4 (67%)
MERV 15+	8 (22%)	4 (50%)	1 (14%)	2 (13%)	1 (17%)
Healthy Building Certification, n (% of Country Total)					
Yes	10 (27%)	1 (13%)	0 (0%)	9 (56%)	0 (0%)
No	27 (73%)	7 (88%)	7 (100%)	7 (44%)	6 (100%)
Green Certification, n (% of Country Total)					
Yes	25 (68%)	8 (100%)	2 (29%)	11 (69%)	4 (67%)
No	12 (32%)	0 (0%)	5 (71%)	5 (31%)	2 (33%)
Sensor Package Type Used in Study, n (% of Country Total)					
Harvard Healthy Buildings	8 (22%)	1 (13%)	5 (71%)	2 (13%)	0 (0%)
Tsinghua IBEM	6 (16%)	6 (75%)	0 (0%)	0 (0%)	0 (0%)
Awair Omni	5 (14%)	0 (0%)	2 (29%)	3 (19%)	0 (0%)
ChemiSense CS-001	1 (3%)	0 (0%)	0 (0%)	1 (6%)	0 (0%)
Tongdy MSD-16	10 (27%)	0 (0%)	0 (0%)	10 (63%)	0 (0%)
Harvard Healthy Buildings + Tsinghua IBEM	1 (3%)	1 (13%)	0 (0%)	0 (0%)	0 (0%)
Harvard Healthy Buildings + Awair Omni	6 (16%)	0 (0%)	0 (0%)	0 (0%)	6 (100%)
Gross area (1,000 m^2), median [range]	5.86 [0.465 – 1,020]	61.2 [2.110 – 201]	29.7 [1.55 – 1,020]	2.93 [0.465 – 546]	2.86 [1.53 – 7.38]
# Occupants during occupied hours, median [range]	400 [42 – 11,000]	650 [135 – 4,520]	3,800 [80 – 5,000]	114 [42 – 11,000]	460 [288 – 600]
Building age (years), median [range]	11 [1 – 120]	5 [2 – 10]	8 [3 – 15]	36 [1 – 120]	23 [3 – 31]
Median building estimated quarterly AER (hour^{-1}), median [range]	0.47 [0.15 – 2.0]	1.0 [0.33 – 1.8]	0.45 [0.15 – 0.79]	0.39 [0.19 – 2.0]	0.54 [0.37 – 0.97]

Distributions of Indoor $PM_{2.5}$ and CO_2 Across Four Countries and Over Time

Country differences in indoor and outdoor $PM_{2.5}$ during work hours from the 37 buildings in this study are shown in Figure 2.1. Indoor $PM_{2.5}$ in the USA and UK was much lower than in China and India, with overall medians of hourly indoor concentrations during work hours of 1.0 $\mu g/m^3$ in the UK, 1.7 $\mu g/m^3$ in the USA, 8.0 $\mu g/m^3$ in India, and 18.0 $\mu g/m^3$ in China. These regional differences were mirrored outdoors. Median outdoor concentrations during work hours were 9.0 $\mu g/m^3$ in the UK, 7.1 $\mu g/m^3$ in the USA, 17.0 $\mu g/m^3$ in India, and 27.0 $\mu g/m^3$ in China.

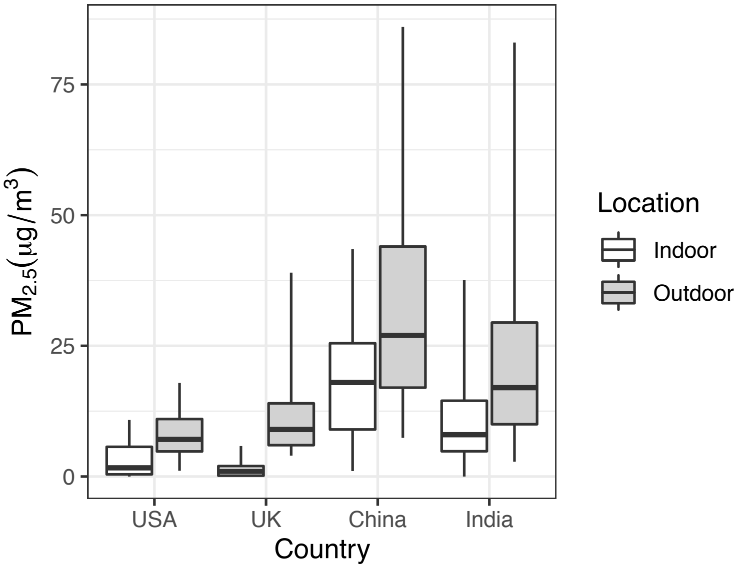

Figure 2.1: Boxplots of indoor and outdoor $PM_{2.5}$ concentrations during work hours by country. Bottom whisker runs from 5th percentile to 25th percentile and top whisker runs from 75th percentile to 95th percentile. Horizontal lines in box represent 25th, 50th, and 75th percentiles.

Median CO_2, indoor $PM_{2.5}$, and outdoor $PM_{2.5}$ concentrations varied by country, time of year, and operating hours at the 37 buildings in this study (Table 2.3). There was some variation of indoor $PM_{2.5}$ levels by three-month period, with the lowest median concentrations in China and India in June – August and highest median concentrations in China, India, and the UK in December – February. In three of the four three-month periods, the median indoor $PM_{2.5}$

concentrations during work hours were lowest in the UK compared to the other three countries. For each three-month period, the median indoor $PM_{2.5}$ concentration during work hours in the UK and the USA was less than 3 $\mu g/m^3$. In China and India, three-month median indoor $PM_{2.5}$ concentrations during work hours exceeded 9 $\mu g/m^3$ with one exception in India during June – August. In China, for each three-month period, the median indoor $PM_{2.5}$ concentration during work hours was between 5.1 and 15.5 times greater than the comparable concentration in the USA. Similarly, in India, for each three-month period, the median indoor $PM_{2.5}$ concentration during work hours was between 2.6 and 20.4 times greater than the comparable concentration in the USA. Trends in indoor $PM_{2.5}$ were consistent with trends in outdoor $PM_{2.5}$, although the three-month median indoor $PM_{2.5}$ concentrations for each country were always lower than the three-month median outdoor $PM_{2.5}$ concentrations, both during work and non-work hours. More detailed summary statistics for indoor and outdoor $PM_{2.5}$ can be found Tables A2 and A3 in Appendix A.

Median (Table 2.3) and 75th percentiles (Table A4 in Appendix A) of hourly device-averaged indoor CO_2 levels during work hours remained lower than 1,000 ppm in all countries in all quarters of the year except for December – February in India. These low to moderate CO_2 levels suggest that the buildings in this study were fairly well ventilated and/or had relatively low occupancies. In China, the 95th percentiles of hourly device-averaged indoor CO_2 during work hours were lower than 1,000 ppm in all four quarters of the year, suggesting that outdoor air ventilation was relatively effective in these buildings. On the other hand, the 95th percentiles of hourly device-averaged CO_2 during work hours were highest in India in all four quarters of the year (ranging from 1,254 ppm to 1,806 ppm). These measurements suggest that the buildings in India were not always well ventilated for their occupancies.

Table 2.3: Summary of hourly measurements of indoor and outdoor $PM_{2.5}$ and CO_2 from buildings in this analysis by country and month, shown separately for work and non-work hours.

Country	Month	Standard Work Hours or Non-Work Hours	CO_2, ppm Median (SD)	Indoor $PM_{2.5}$, $\mu g/m^3$ Median (SD)	Outdoor $PM_{2.5}$, $\mu g/m^3$ Median (SD)	# of $PM_{2.5}$ Datapoints
China	Mar – May	Standard work hours	511 (99)	18.3 (15.5)	27.0 (24.7)	11,194
		Non-work hours	423 (59)	17.2 (9.5)	28.0 (24.6)	29,234
	Jun – Aug	Standard work hours	567 (126)	11.8 (15.2)	20.0 (16.0)	10,747
		Non-work hours	421 (65)	9.9 (7.9)	19.0 (15.7)	29,230
	Sep – Nov	Standard work hours	532 (122)	20.0 (14.2)	28.0 (24.5)	10,314
		Non-work hours	432 (75)	18.3 (10.8)	28.0 (24.3)	25,573
	Dec – Feb	Standard work hours	552 (184)	21.7 (16.6)	35.0 (31.0)	10,714
		Non-work hours	431 (82)	20.8 (11.9)	35.0 (30.4)	26,923
India	Mar – May	Standard work hours	630 (441)	17.5 (11.5)	32.2 (30.7)	485
		Non-work hours	473 (270)	23.2 (12.8)	37.0 (36.2)	1,055
	Jun – Aug	Standard work hours	753 (316)	6.0 (4.4)	13.0 (24.1)	3,012
		Non-work hours	460 (185)	8.8 (7.3)	12.2 (23.7)	8,033
	Sep – Nov	Standard work hours	711 (320)	9.2 (10.4)	16.9 (18.0)	2,502
		Non-work hours	470 (206)	12.0 (14.5)	17.1 (25.4)	6,199
	Dec – Feb	Standard work hours	1058 (444)	28.6 (40.6)	77.3 (57.1)	534
		Non-work hours	560 (221)	45.2 (27.1)	75.0 (53.8)	956
UK	Mar – May	Standard work hours	750 (184)	1.0 (11.3)	10.0 (10.3)	13,282
		Non-work hours	434 (71)	1.5 (4.1)	10.0 (10.0)	36,759
	Jun – Aug	Standard work hours	796 (171)	0.8 (1.6)	7.0 (3.7)	9,404
		Non-work hours	433 (99)	1.0 (6.4)	7.0 (3.5)	24,574
	Sep – Nov	Standard work hours	790 (183)	0.0 (2.3)	7.0 (8.8)	1,320
		Non-work hours	447 (79)	0.2 (3.1)	7.0 (6.7)	3,543
	Dec – Feb	Standard work hours	740 (181)	1.8 (10.7)	14.0 (14.7)	4,674
		Non-work hours	456 (91)	3.4 (4.7)	20.0 (13.0)	11,311
USA	Mar – May	Standard work hours	578 (177)	1.2 (3.7)	7.0 (5.0)	21,788
		Non-work hours	444 (125)	1.8 (3.6)	7.5 (6.9)	54,226
	Jun – Aug	Standard work hours	604 (197)	2.3 (3.6)	8.0 (6.3)	22,906
		Non-work hours	458 (137)	2.9 (4.3)	8.3 (6.1)	61,230
	Sep – Nov	Standard work hours	589 (196)	1.7 (4.2)	7.0 (5.6)	15,213
		Non-work hours	443 (135)	2.7 (4.3)	7.0 (5.5)	38,298
	Dec – Feb	Standard work hours	617 (208)	1.4 (4.7)	7.0 (6.1)	17,810
		Non-work hours	441 (145)	1.7 (4.3)	7.2 (6.2)	45,223

Association between Outdoor and Indoor PM$_{2.5}$ Levels

The results of the generalized additive mixed models are shown in Table 2.4. In separate models for work and non-work hours, the natural logarithm of indoor PM$_{2.5}$ was positively and significantly associated with outdoor PM$_{2.5}$ (p<0.0001). During work hours, a 10 μg/m^3 increase in outdoor PM$_{2.5}$ was associated with a 19.9% (95% confidence interval [CI]: +19.5%, +20.3%) increase in the expected concentration of indoor PM$_{2.5}$, controlling for building age, MERV rating, quarterly AER, country, and datetime (p<0.0001). For example, for a building where the indoor PM$_{2.5}$ concentration is identical to the median concentration during work hours in China (18.0 μg/m^3), a 10 μg/m^3 increase in outdoor PM$_{2.5}$ is expected to be associated with a 3.6 μg/m^3 increase in indoor PM$_{2.5}$. For a building where the indoor PM$_{2.5}$ concentration is identical to the median concentration during work hours in USA (1.7 μg/m^3), a 10 μg/m^3 increase in outdoor PM$_{2.5}$ is expected to be associated with a 0.3 μg/m^3 increase in indoor PM$_{2.5}$.

Table 2.4: Results, shown as percent changes in indoor PM$_{2.5}$, from the model predicting the natural logarithm of indoor PM$_{2.5}$ using data from buildings with mechanical or mixed-mode ventilation and filtration, with random intercepts for building and for device and with a spline on datetime.

	Standard Work Hours		**Non-Work Hours**	
	% change (95% CI)	*p-value*	% change (95% CI)	*p-value*
Outdoor PM$_{2.5}$ (+10 μg/m^3)	+19.9% (+19.5%, +20.3%)	<0.0001	+23.4% (+23.1%, +23.6%)	<0.0001
Building age (+1 year)	+1.3% (+0.5%, +2.1%)	0.002	+1.2% (-0.1%, +2.5%)	0.07
Level of Filtration (Reference = MERV 7-12)				
MERV 13-14	-30.9% (-55.0%, +6.2%)	0.09	+20.6% (-43.6%, +158%)	0.63
MERV 15+	-39.4% (-62.0%, -3.4%)	0.04	-37.4% (-74.1%, +51.4%)	0.30
AER (Reference = Quartile 1)				
Quartile 2	-30.0% (-31.6%, -28.3%)	<0.0001		
Quartile 3	-29.3% (-31.2%, -27.4%)	<0.0001		
Quartile 4	-13.6% (-16.1%, -11.2%)	<0.0001		
Country (Reference = USA)				
UK	+4.9% (-36.1%, +72.2%)	0.85	-6.3% (-65.3%, +153%)	0.90
China	+735% (+364%, +1403%)	<0.0001	+791% (+216%, +2416%)	<0.0001
India	+653% (+313%, +1274%)	<0.0001	+657% (+170%, +2024%)	0.0001

During non-work hours, a 10 μg/m^3 increase in outdoor PM$_{2.5}$ was associated with an even higher 23.4% (95% CI: +23.1%, +23.6%) increase in the expected concentration of indoor PM$_{2.5}$, controlling for building age, MERV rating, country, and datetime (p<0.0001). For example, for a building where the indoor PM$_{2.5}$ concentration is identical to the median concentration during non-work hours in China (16.2 μg/m^3), a 10 μg/m^3 increase in outdoor PM$_{2.5}$ is expected to be associated with 3.8 μg/m^3 increase in indoor PM$_{2.5}$. For a building where the indoor PM$_{2.5}$ concentration is identical to the median concentration during non-work hours in the USA (2.2 μg/m^3), a 10 μg/m^3 increase in outdoor PM$_{2.5}$ is expected to be associated with 0.5 μg/m^3 increase in indoor PM$_{2.5}$.

Association between Filtration and Indoor PM$_{2.5}$ Levels

Indoor and outdoor PM$_{2.5}$ concentrations during work hours by the MERV rating of the filter in the building where the measurements were collected are shown in Figure 2.2. The results of the generalized additive mixed models (Table 2.4) show suggestive and statistically significant evidence that office buildings' filter ratings were associated with concentrations of indoor PM$_{2.5}$. When filters with higher MERV ratings were used, indoor PM$_{2.5}$ tended to be lower. During work hours, the expected concentration of indoor PM$_{2.5}$ was approximately 39.4% (95% CI: -62.0%, -3.4%) lower in buildings with MERV 15+ filters than in buildings with MERV 7-12 filters, controlling for outdoor PM$_{2.5}$, building age, building AER, country, and datetime (p=0.04). During work hours, the expected concentration of indoor PM$_{2.5}$ was approximately 30.9% (95% CI: -55.0%, +6.2%) lower in buildings with MERV 13-14 filters than in buildings with MERV 7-12 filters, controlling for outdoor PM$_{2.5}$, building age, building AER, country, and datetime (p=0.09). For example, if the indoor PM$_{2.5}$ concentration in a building with a MERV 7-12 filter was equal to the median concentration during work hours in China (18.0 μg/m^3), a co-located identical building that had a MERV 13-14 filter would be expected to have an indoor PM$_{2.5}$ concentration during work hours of only 12.4 μg/m^3.

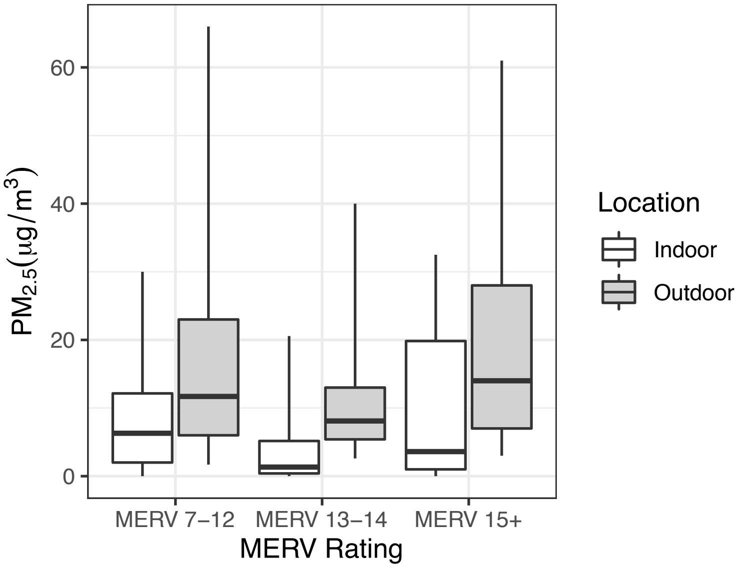

Figure 2.2: Boxplots of indoor and outdoor PM$_{2.5}$ concentrations during work hours by building MERV rating. Bottom whisker runs from 5th percentile to 25th percentile and top whisker runs from 75th percentile to 95th percentile. Horizontal lines in box represented 25th, 50th, and 75th percentiles.

During non-work hours, indoor PM$_{2.5}$ was not significantly associated with building filtration and standard errors for the effect estimates of the association between filtration and indoor PM$_{2.5}$ were larger during non-work hours than during work hours. These results are likely due to more variation in ventilation operations during non-work hours than during work hours, perhaps due to buildings scaling back their ventilation operations to different degrees or perhaps due to our definition of non-work hours inadvertently including some work hours when buildings were occupied.

Association between Air Exchange Rate and Indoor $PM_{2.5}$ Levels

The results of the generalized additive mixed model for work hours (Table 2.4) show that office buildings' AERs were significantly associated with indoor $PM_{2.5}$ concentrations, with buildings where quarterly AERs exceeded the 25th percentile (0.31 $hour^{-1}$) having lower indoor $PM_{2.5}$ than buildings where quarterly AERs were lower than the 25th percentile. Compared to buildings with quarterly AERs in the first quartile (<0.31 $hour^{-1}$), the expected concentration of indoor $PM_{2.5}$ during work hours was approximately 30.0% (95% CI: -31.6%, -28.3%) lower in buildings with quarterly AERs in the second quartile (0.31 $hour^{-1}$ – 0.47 $hour^{-1}$), 29.3% (95% CI: -31.2%, -27.4%) lower in buildings in the third quartile (0.47 $hour^{-1}$ – 0.84 $hour^{-1}$), and 13.6% (95% CI: -16.1%, -11.2%) lower in buildings in the fourth quartile (>0.84 $hour^{-1}$), controlling for outdoor $PM_{2.5}$, building age, MERV rating, country, and datetime ($p<0.0001$).

Model Variances

In the model using data from work hours, the variances of the random intercepts for building and for $PM_{2.5}$ sensor and of the residuals were 3.94×10^{-5}, 1.52, and 0.874, respectively. These variances indicate that the variables included in the model explained essentially all of the variability in the natural logarithm of indoor $PM_{2.5}$ concentrations between buildings in the study. By contrast, there was much more unexplained variation between sensors within a building; 63% of the residual variability in the modeled natural logarithm of indoor $PM_{2.5}$ concentrations unexplained by the model covariates was explained by differences between sensors within buildings. During non-work hours, the variances of the random intercepts for building and for sensor and of the residuals were 0.770, 0.672, and 0.993, respectively. The notable increase in variance at the building level during non-work hours compared to work hours suggests that differences in indoor $PM_{2.5}$ concentrations between buildings are only well explained by the building characteristics in the model when building systems are in use.

Discussion

The results of this analysis suggest that indoor $PM_{2.5}$ concentrations are generally lower than outdoor $PM_{2.5}$ concentrations in buildings with mechanical ventilation and filtration. Nonetheless, in countries with high outdoor $PM_{2.5}$ levels, indoor $PM_{2.5}$ concentrations sometimes exceeded health-based exposure guidelines. For example, in India and China, 17% and 27%, respectively, of daily mean (during work hours only) indoor $PM_{2.5}$ concentrations in these data exceeded the WHO average 24-hour exposure guideline of 25 $\mu g/m^3$.[81] The results of this analysis demonstrate that buildings with high filter efficiencies had statistically significantly lower indoor $PM_{2.5}$ than buildings with standard filter efficiencies across the four countries studied. This result suggests that filters can reduce indoor $PM_{2.5}$ exposure in regions with high and low outdoor $PM_{2.5}$ exposures, both of which are important because there is no known threshold below which $PM_{2.5}$ exposure is thought to be safe[81] and since harmful effects of $PM_{2.5}$ have been seen for short- and long-term exposures to relatively low and commonly-encountered $PM_{2.5}$ concentrations.[7,62,82] These findings suggest that office buildings should consider operating their ventilation systems with filters with the highest MERV rating that can function in their system to provide the strongest health benefit for their occupants. The expected health impact of enhanced filtration includes improved health outcomes associated with acute and chronic $PM_{2.5}$ exposures including cardiovascular and respiratory health.

Impact of Mechanical System Operation, Filtration, and Air Exchange Rate on Indoor $PM_{2.5}$ Concentrations

The results of the generalized additive mixed models indicate that indoor $PM_{2.5}$ increases more quickly as outdoor $PM_{2.5}$ increases during non-work hours compared with work hours. This analysis also found that buildings that used filters with ratings of at least MERV 13 had lower indoor $PM_{2.5}$ concentrations than buildings that used filters with ratings of MERV 7-12 during work hours, but not during non-work hours. These results suggest that filters are effective to reduce indoor $PM_{2.5}$ in occupied buildings during operating hours. These results support a prior finding that indoor $PM_{2.5}$ was significantly lower during work hours compared to non-work hours in three of six buildings studied in China, though it is not clear what level of filtration was present in these buildings.[83]

This analysis found that quarterly AERs in the second, third, and fourth quartiles were associated with reductions in average indoor $PM_{2.5}$ concentrations compared to quarterly AERs in the first quartile. While this finding seems to contradict prior work that found higher ratios of indoor $PM_{2.5}$ to outdoor $PM_{2.5}$ (I/O ratios) as ventilation rates increased from 1.0 hour^{-1} to 2.4 hour^{-1} to 5.4 hour^{-1} in experiments with MERV 8, MERV 14, and MERV 15 filters, the results in our analysis were not necessarily comparable with these prior results because all four quartiles in our analysis included AERs lower than the lowest rate of 1.0 hour^{-1} examined previously.[68] Our AER estimates may be underestimates of the true AERs in the participating buildings if they were influenced by employees still in the building or if they were influenced by evening changes in ventilation system operations. In our results, the most notable finding was that $PM_{2.5}$ tended to be higher when quarterly AERs were in the first quartile (<0.31 hour^{-1}) compared to when quarterly AERs were higher; it is possible that these periods with very low AERs represent periods when outdoor air ventilation was so low that indoor $PM_{2.5}$ could accumulate due to indoor sources of $PM_{2.5}$ that were never diluted due to the lack of input of filtered outdoor air. In any case, our results agree with prior work that found that adjusting filters from MERV 8 to MERV 14 or 15 had a bigger impact on reducing indoor $PM_{2.5}$ than adjusting the outdoor air ventilation rate did.[68] In this analysis, MERV 13-14 filters and MERV 15+ filters reduced indoor $PM_{2.5}$ by 30.9% and 39.4%, respectively, compared to MERV 7-12 filters, while the effects of quarterly AER (the difference between the first and other quartiles) ranged from -13.6% to -30.0%.

Comparison of Indoor $PM_{2.5}$ Concentrations and the Relationship between Indoor and Outdoor $PM_{2.5}$ with Other Studies

In the Global CogFx Study and in prior studies of $PM_{2.5}$ in office buildings in the USA, Europe, and Asia, outdoor $PM_{2.5}$ concentrations generally exceeded indoor $PM_{2.5}$ concentrations.[73,83–86] The indoor $PM_{2.5}$ values measured in USA, UK, and Chinese buildings in this analysis were also somewhat lower than prior measurements in USA, European, and Chinese office buildings. In the BASE study (in 1994-1998) in the USA, approximately 75% of one-workday integrated indoor $PM_{2.5}$ concentrations during business hours were less than 10 μg/m^3.[73] By comparison, approximately 93% of hourly indoor $PM_{2.5}$ measurements during work hours were less than 10 μg/m^3 in data from USA buildings in this analysis. Similarly, a recent study of 37 small and medium commercial buildings, including nine offices, in California[86] found that the median one-day integrated indoor $PM_{2.5}$ concentration in offices during business hours was 6.4 μg/m^3 which exceeds the median indoor $PM_{2.5}$ concentration of 1.7 μg/m^3 in USA office buildings in our analysis of data from the Global CogFx Study. These differences may be due to differences between the buildings in the studies' convenience samples. For example, compared to buildings in this analysis which all had filter efficiencies of MERV 7 or higher, the California offices had low filter efficiencies (i.e. MERV 4 or lower).[86] These differences could also be due to the 43% reduction in the national average outdoor $PM_{2.5}$ over the two decades that have elapsed between the BASE study (in 1994-1998) and the Global CogFx Study (in 2018-2020)[87] because outdoor $PM_{2.5}$ can be an important source of indoor $PM_{2.5}$.[69,84,88]

In a study conducted on 13 floors of six buildings in Chengdu, China during autumn 2016, building floor average indoor $PM_{2.5}$ levels over the full monitoring period ranged from 35 $\mu g/m^3$ to 97 $\mu g/m^3$.[83] By contrast, the mean of all hourly indoor measurements during September – November in the three Chengdu buildings in our study was only 16.8 $\mu g/m^3$. Interestingly, the mean I/O ratios in the 2016 measurements ranged from 0.38 to 0.97;[83] this range includes the mean I/O ratio for all the hourly measurements in September – November in the three Chengdu buildings in our study of 0.41. Though the absolute indoor $PM_{2.5}$ concentrations in our study were lower than those in the 2016 study, the overlap of our I/O ratio with the 2016 study's range of I/O ratios suggests that the differences may be due to elevated outdoor $PM_{2.5}$ concentrations during the 2016 study compared to our study. The differences could also be due to differences between the buildings in the studies' convenience samples, as the Chinese buildings in our study all had green certifications and tended to have high filtration efficiencies.

Prior research investigating relationships between indoor and outdoor $PM_{2.5}$ has found indoor $PM_{2.5}$ concentrations to be moderately correlated with outdoor $PM_{2.5}$ concentrations. For example, the 20-building European OFFICAIR study found a correlation of 0.74 between integrated 100-hour measurements of indoor and outdoor $PM_{2.5}$ concentrations in two seasons.[85] Given the influence that building ventilation practices are expected to have on the relationship between indoor and outdoor $PM_{2.5}$, this high degree of correlation suggests that the buildings in the OFFICAIR study may have had air filters with relatively low filter efficiencies, that infiltration occurred overnight (while $PM_{2.5}$ measurements continued overnight), or that open windows allowed unfiltered outdoor air to enter (OFFICAIR windows were generally closed, but open in some buildings for part of the study). In the USA-based BASE study, the correlation between integrated 8-hour measurements of indoor and outdoor $PM_{2.5}$ concentrations in 100 buildings was only 0.44.[73] The authors of the BASE study suggested that this correlation was not higher due to the decoupling of indoor and outdoor $PM_{2.5}$ concentrations by filtration. The Global CogFx Study data corroborate this finding of the BASE study. In this study, the Spearman correlation between building daily average concentrations of indoor and outdoor $PM_{2.5}$ measured during work hours was 0.09 in USA buildings, 0.41 in UK buildings, 0.40 in China buildings, and 0.67 in India buildings. Although the larger ranges of indoor and outdoor $PM_{2.5}$ in China and India compared to the USA and the UK likely contribute to the higher correlations in buildings in those countries, these low to moderate correlations support the authors of the BASE study's suggestion that the operation of ventilation systems decouples indoor and outdoor $PM_{2.5}$ concentrations to a degree.

Comparison of the Impact of Filtration with Other Studies

Only a limited number of prior studies have examined the impact of MERV rating on concentrations of indoor pollutants in situ, and even fewer of these studies have done so in multiple buildings. In an experiment that tested three filter efficiencies in a single building in Philadelphia, Pennsylvania, $PM_{2.5}$ I/O ratios were lower when MERV 14 and MERV 15 filters were used compared to MERV 8 filters at all three AERs tested.[68] In 40 measurements in 37 commercial buildings in California, including offices, retail establishments, restaurants, and gas station convenience stores, the ratio of measured indoor black carbon (a component of $PM_{2.5}$) to outdoor black carbon was lower in the 12 buildings with MERV 6-8 filters than in the 23 buildings with filter ratings of MERV 4 or lower, though this difference was not significant.[86] Importantly, this California analysis also did not control for any building characteristics that could be relevant. Consequently, their result may not necessarily indicate that higher MERV ratings result in less indoor black carbon; for example, if one building type was more likely to have low-efficiency filters and more likely to have higher ratios of indoor to outdoor black carbon perhaps due to re-suspension of settled black carbon by occupant movement, it is possible that there would appear to be a relationship between filter efficiency and black carbon when none existed. Our analysis addressed this issue and found that filter efficiency was associated with reduced indoor $PM_{2.5}$ after controlling for outdoor $PM_{2.5}$, building characteristics, and datetime.

Public Health Impact of Improved Filtration

Reducing indoor $PM_{2.5}$ levels through filtration may reduce the risks of adverse outcomes of $PM_{2.5}$ exposure for office workers. Although the relationship between indoor $PM_{2.5}$ concentrations and various health outcomes is relatively understudied, we can draw on research that links outdoor $PM_{2.5}$ with health outcomes. For example, the recently-published Global Exposure Mortality Model used data from 41 cohort studies in 16 countries to develop age-specific hazard ratios for long-term outdoor $PM_{2.5}$ exposures and various causes of death.[7] Under the assumptions that the relationship between outdoor $PM_{2.5}$ and mortality from the Global Exposure Mortality Model represents the relationship between in-office $PM_{2.5}$ and mortality, upgrading a filter from MERV 7-12 to MERV 15+ in a building where indoor $PM_{2.5}$ is 18.0 $\mu g/m^3$ (the median indoor concentration during work hours in Chinese buildings in this study) would be expected to reduce the hazard ratio for mortality from non-communicable diseases and lower respiratory infections among 25- to 29-year-olds from approximately 1.21 to 1.14. Similarly, upgrading a filter from MERV 7-12 to MERV 13-14 in a building where indoor $PM_{2.5}$ is 18.0 $\mu g/m^3$ would be expected to reduce the hazard ratio for mortality from non-communicable diseases and lower respiratory infections among 25- to 29-year-olds from approximately 1.21 to 1.15. In reality, these reductions in the hazard ratio may be underestimates if $PM_{2.5}$-relatated mortality is more strongly related with indoor $PM_{2.5}$ than it is with outdoor $PM_{2.5}$; on the other hand, they may be overestimates because workers will only be helped by the in-office $PM_{2.5}$ reduction during the approximately 20%-25% of their time they spend at their offices. In addition to reducing the likelihood of health problems caused by chronic exposure to $PM_{2.5}$, improving office filtration could also reduce the harmful health effects due to acute exposures to $PM_{2.5}$. Subclinical effects of acute $PM_{2.5}$ exposure, such as changes in cardiac function[89] and clinical effects of acute $PM_{2.5}$ exposure, such as respiratory or cardiovascular hospitalization,[61] would be expected to be improved with higher levels of filtration. While effects of chronic exposures may take years to appear, acute exposures on the order of minutes, hours, or a day can occur during a single workday, so the benefits of indoor $PM_{2.5}$ mitigation on these outcomes are more certain to be realized.

A filter rating of at least MERV 8 is recommended by ASHRAE for outdoor air being distributed to occupied spaces in areas where the PM_{10} national standard for outdoor air is exceeded.[24] A filter rating of at least MERV 13 for outdoor air being distributed to occupied spaces is included in the optional United States Green Building Council's Leadership in Energy and Environmental Design (LEED) Enhanced Indoor Air Quality Strategies credit[90] and is a prerequisite in the Air Filtration category for achieving the WELL Building Standard's healthy building certification.[91] The MERV 13 threshold used by the LEED and WELL rating systems is supported by our result that buildings with filters rated MERV 13-14 had 30.9% (95% CI: -55.0%, +6.2%) lower indoor $PM_{2.5}$ than buildings with filters rated MERV 7-12, controlling for outdoor $PM_{2.5}$, building characteristics, and datetime. Since there is no known safe threshold of exposure to $PM_{2.5}$,[81] the additional reductions in $PM_{2.5}$ achieved by using filters with ratings of at least MERV 13 would promote the health of office workers in places with high and low concentrations of outdoor $PM_{2.5}$.

Effect of Potential Measurement Error of Indoor $PM_{2.5}$ Concentrations

Recent advancements in low-cost sensor technology have opened up new opportunities for monitoring indoor environmental quality. Due to its global and distributed scale and one-year duration, the Global CogFx Study was only feasible with the use of low-cost laser-based $PM_{2.5}$ sensors. Prior work on various types of low-cost $PM_{2.5}$ sensors indicates that there is often a high degree of consistency in measurements made by multiple sensors of the same type when they are collocated, while sensors of different types may exhibit more variation.[92–95] In some circumstances, these sensors are less accurate than research-grade instruments and prior characterization of sensors similar to those in the Global CogFx Study found that sensor measurements can differ from research-grade measurements by up to a factor of two.[95,96] It has also been shown that the characteristics of the $PM_{2.5}$ being measured, such as the size distribution, impact the degree of error in the measurement. For example, it is common for some low-cost sensors to underreport $PM_{2.5}$ concentrations when measuring $PM_{2.5}$ that is mostly comprised of particles with diameters of less than approximately 0.3 μm. One study of six types of low-cost $PM_{2.5}$ sensors found that they did not respond to particle sources with diameters smaller than 0.25 μm.[95] The specifications for the sensors used in this study (Table 2.1) indicate that errors of up to 10-15 $\mu g/m^3$ could be present in the measured indoor $PM_{2.5}$ concentrations in this analysis. However, in our analysis, measurement error due to differences between the multiple sensor types or due to underreporting of certain particle sizes can only bias our result showing lower indoor $PM_{2.5}$ concentrations in buildings with more efficient filters if the degree of error differs across the three filtration categories (i.e. if differential measurement error in indoor $PM_{2.5}$ with respect to MERV ratings is present). We will briefly consider whether this was the case for the two potential sources of bias mentioned.

Differential measurement error of indoor $PM_{2.5}$ with respect to filtration categories could occur if specific sensor types with different degrees of bias were used in buildings in each filtration category (i.e. if sensor type and MERV rating were not independent). For our data, a chi-squared test of whether sensor types used in buildings were independent from MERV rating categories of the buildings (MERV 7-12, MERV 13-14, or MERV 15+) failed to reject the null hypothesis that sensor type and filtration level were independent (χ^2=10.8, p=0.21). This lack of significant association between filtration and study sensor type was expected, as the research team did not know the buildings' filtration levels when choosing which sensor to deploy. Since sensor type and filtration level appear to be independent, the measurement error in indoor $PM_{2.5}$ measurements due to different sensor types is expected to be nondifferential with respect to filtration level and is not expected to result in any systematic bias in our model results, though it may result in larger standard errors.

Differential measurement error of indoor $PM_{2.5}$ with respect to filtration category could also occur if the degree of undercounting of particles of certain sizes, say smaller than approximately 0.30 μm, differed between buildings with different filter efficiencies. While 0.30 μm is the minimum particle diameter that is considered when assigning a MERV rating to a filter, office buildings with more efficient filters are expected to have lower concentrations of particles of all diameters including those less than 0.30 μm.[97,98] Consequently, though some low-cost $PM_{2.5}$ sensors may underreport $PM_{2.5}$ because they underreport concentrations of certain particle sizes (e.g. smaller than approximately 0.30 μm), it is expected that the ratio of measured $PM_{2.5}$ to true $PM_{2.5}$ due to this undercounting is similar for all filtration categories. In other words, the percent error in $PM_{2.5}$ measurement due to undercounting certain particle sizes does not depend on the level of filtration in buildings. As a result, we do not expect that this error in $PM_{2.5}$ measurements will result in a biased estimate of the impact of filtration on indoor $PM_{2.5}$.

In summary, although measurement error may be present in the indoor $PM_{2.5}$ measurements used in this analysis, it is not expected to be differential with respect to the main covariate of interest. Therefore, our model results are not expected to be biased, though they may suffer from inflated standard errors.

Strengths & Limitations

Due to the scale of this study, study team members did not visit all of the buildings that participated in the study. Consequently, this study is limited by incomplete knowledge of all relevant variables that could impact indoor $PM_{2.5}$ concentrations, such as proximity of building air inlets to sources of pollution, use of portable air cleaners or open windows, configuration of ventilation systems including filter locations, total recirculated and outdoor airflows, locations and frequency of use of indoor $PM_{2.5}$ sources, and deposition and resuspension rates of indoor $PM_{2.5}$. Similarly, we did not measure outdoor air ventilation in each building which could have resulted in more accurate estimates of quarterly AERs than the CO_2-based estimates that were used in this study. On the other hand, by using continuous CO_2 measurements to estimate AERs, we were able to build estimates for each three-month quarter of the year to account for variation across the year. Finally, this analysis made the assumption that work hours in each office were contained within the 9:00 – 17:00 window on weekdays and that ventilation systems typically operated normally during these hours; if this assumption is wrong, our estimates of the impact of filtration during work hours may be biased toward no effect.

Nonetheless, this study has significant advantages over previous analyses of $PM_{2.5}$ measurements in office buildings. First, this study measured $PM_{2.5}$ in many buildings in widely varying cultural and geographical contexts making the results of this work more generalizable than prior work examining fewer than 10 buildings generally located in the same city or region.[69,99–104] Second, this study measured $PM_{2.5}$ in multiple locations in each building, ensuring that the measurements accurately represented the spectrum of exposures within each office; most prior studies have not accounted for within-building variation because they only measured $PM_{2.5}$ in a single indoor location or they aggregated $PM_{2.5}$ measurements collected at a handful of indoor locations.[73,99,102,105] Third, this study measured $PM_{2.5}$ continuously over a full year to understand how office workers' exposures varied between work and non-work hours and across the year; many prior studies did not address variability in exposure over time because they only made spot or integrated measurements of $PM_{2.5}$ during normal business hours.[73,99]

Conclusions

This study suggests that office building operations can protect against exposure to air pollution indoors. In all four countries in this study, indoor $PM_{2.5}$ was generally lower than outdoor $PM_{2.5}$; nonetheless, indoor $PM_{2.5}$ still exceeded WHO health-based exposure guidelines in some instances in countries with elevated outdoor $PM_{2.5}$. Even when indoor $PM_{2.5}$ is below exposure guidelines, it is still desirable to reduce concentrations in office buildings as much as possible because the duration of office workers' exposure to pollutants in their workplaces is substantial and because there is no known safe threshold for $PM_{2.5}$ exposure. Building operations can impact how much $PM_{2.5}$ of outdoor origin comes indoors and how long $PM_{2.5}$ of indoor origin remains present. The results of this study suggest that filters, in particular, are an intervention that can reduce $PM_{2.5}$ indoors, as buildings in this study with MERV 13 or higher filters had lower indoor $PM_{2.5}$ than buildings with MERV 7-12 filters during work hours, controlling for relevant variables. This effect was strongest for the filters with the highest ratings, MERV 15+. As long- and short-term $PM_{2.5}$ exposures have various harmful impacts on people's health and wellbeing, buildings should consider upgrading filters beyond what is considered standard to protect the health of their occupants.

CHAPTER 3: INDOOR HUMIDITY LEVELS AND ASSOCIATIONS WITH REPORTED SYMPTOMS IN OFFICE BUILDINGS

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Author Contributions

E.R.J conceptualized this analysis, contributed to carrying out the study activities, developed the statistical models, performed the formal analysis, and prepared the manuscript. J.G.C.L. and A.S.Y. contributed to carrying out the study activities and provided critical revision of the manuscript. B.A.C. and J.D.S. provided critical revision of the manuscript. J.G.A. acquired financial support for this project, provided critical review of the manuscript, and supervised the project.

Abstract

Moderate indoor relative humidity (RH) levels (i.e. 40%-60%) minimize transmission and viability of some viruses (e.g. SARS-CoV-2), maximize human immune defense against viral infection, and minimize health risks from mold growth and dust mites. As workplaces update their operations to promote occupant health and comfort in the wake of the COVID-19 pandemic, they may consider controlling indoor RH, yet uncertainties exist about typical RH levels in offices globally and about the potential independent impacts of RH levels on worker health. To examine this, we leveraged one year of indoor RH measurements in 43 office buildings in China, India, Mexico, Thailand, the United Kingdom, and the United States, and corresponding self-report symptom data from 227 office workers in the subset of buildings in India, the United Kingdom, and the United States, collected in 2018-2020. In the buildings in this study, 42% of measurements during 9:00 – 17:00 on weekdays throughout the year were less than 40% RH and 7% were greater than 60% RH. Indoor RH levels tended to be lower in less tropical regions, in winter months, when outdoor RH or temperature was low, and late in the workday. We found that higher indoor RH levels across the range of 14%-70% RH were suggestively or significantly associated with lower odds of reporting three symptoms (including two mucous membrane symptoms) among females and two symptoms among males. Among females, odds ratios of reporting dryness or irritation of the eyes, throat, and skin as RH increased by ten percentage points were 0.74 (95% confidence interval [CI]: 0.52, 1.06), 0.60 (95% CI: 0.42, 0.86), and 0.46 (95% CI: 0.29, 0.75), respectively, in models adjusted for indoor temperature, gender, country, and day of year. Among males, the adjusted odds ratios of reporting dry skin and unusual fatigue as RH increased by ten percentage points were 0.58 (95% CI: 0.33, 1.02) and 0.58 (95% CI: 0.36, 0.95), respectively. These RH-symptom relationships

were linear across the range of indoor RH levels measured over one year in three countries, with no observed RH threshold where symptom reporting plateaued. These results suggest that interventions to increase humidity to the acceptable range of moderate RH in office buildings may be useful, particularly during winter, in less tropical climates, and late in the workday, to reduce health risks from certain viruses and indoor contaminants that are exacerbated at low indoor RH and to alleviate occupant symptoms.

Introduction

Office buildings can impact the health and well-being of office workers, particularly because of the substantial amount of time these workers spend in their workplaces. Humidity is one indoor parameter that can influence multiple aspects of office workers' health and comfort, with implications for their productivity.

One way humidity impacts health is by influencing the spread of viral diseases indoors, as low and high humidity can support viral viability, while low humidity supports viral transmission and weakens humans' immune defenses. Several important viruses, including influenza and SARS-CoV-2, are more viable at very low and very high relative humidity (RH) levels compared to intermediate RH levels.[37–43] Lower RH levels also cause more evaporation of airborne virus-carrying respiratory droplets that have been emitted by an infectious person, and the resulting smaller droplets can remain airborne (i.e. available to be inhaled by and to infect other people) for longer periods of time before settling due to gravity.[39,41] Finally, low RH also impedes mucociliary clearance, an important mechanism for removal of inhaled particles and viruses from the respiratory tract; mucociliary clearance has been found to be faster and thus more effective at intermediate RH levels between 40% and 50% than at levels below 10%.[106,107]

High humidity can promote the presence of indoor contaminants that harm occupant health, while low humidity can increase reported symptoms. For example, high RH levels, typically greater than 60-75% RH, can lead to mold growth,[44,45] which can negatively affect respiratory health by triggering allergic reactions or exacerbating asthma.[45,108] Indoor humidity can also affect emissions of volatile compounds from building materials which may impact occupants' perceptions of indoor air quality.[109,110] On the other hand, several studies report that dry indoor environments can lead to increased reports of dry or irritated eyes, dry skin, and lower and upper respiratory symptoms such as wheeze and sinus congestion.[46–49] To minimize the harmful impacts of viruses, indoor contaminants, and indoor dryness on building occupants, maintaining a moderate indoor RH level between approximately 40% and 60% RH is optimal.

However, there is a general lack of knowledge about how RH levels in real-world workplaces vary over time and geography and how RH might differentially affect the health of different populations. Prior research into the effect of RH on office workers' comfort and health generally compares effects at a few discrete RH values that may not capture the full shape of the relationship between RH and occupant health and may not be generalizable to regions with RH levels that do not match the specific levels under study. Furthermore, this body of prior research does not always distinguish the effect of RH from that of temperature, and it generally has not investigated gender differences in how RH might impact symptoms (even though it has been observed that healthy women report more symptoms than healthy men[111,112]) or considered diverse populations from whom we can generalize to global workers (much of the relevant work has occurred in Nordic countries[46]).

Our goal was to characterize workplace RH levels over one year in 43 office buildings in six countries around the world and to determine how these observed RH levels affected the reported health of 227 male and female office workers. We first evaluated the range of humidity values in these office buildings between 2018 and 2020 to see when and where buildings tended to have intermediate indoor RH values (i.e. 40%-60%) that are protective against respiratory virus transmission and indoor contaminants and that promote human health (e.g. fewer symptoms, better immune defenses against respiratory pathogens). We then identified the building features associated with indoor humidity levels and evaluated how measured indoor humidity levels from offices in India, the United Kingdom, and the United States were associated with occupant-reported symptoms.

Materials & Methods

Study Design

This analysis used data from the Global CogFx Study, which was a one-year study of office workers in 43 office buildings in China, India, Mexico, Thailand, the United Kingdom (UK), and the United States (USA) between 2018 and 2020. Of the 43 buildings, eight were in China (participated 5/2018 – 8/2019; three in Chengdu, three in Shanghai, and two in Zhuhai), 10 were in India (participated 11/2018 – 11/2019; five in Bengaluru and one each in Chennai, Gurugram, Hyderabad, Mumbai, and Pune), one was in Mexico (participated 3/2019 – 3/2020; in Culiacán), one was in Thailand (participated 2/2019 – 2/2020; in Bangkok), six were in the UK (participated 7/2018 – 7/2019; two in Croydon and one each in Birmingham, Cambridge, London, and Sheffield), and 17 were in the USA (participated 10/2018 – 3/2020; two in Chicago, two in Los Angeles, two in San Francisco, and one each in Boston, Clearwater, Cleveland, Denver, Minneapolis, New York City, Omaha, Overland Park, Phoenix, Seattle, and Washington DC). These buildings were a convenience sample of high quality commercial office spaces. In each office building, a single company participated in study activities. These companies were knowledge work companies with at least 10 employees who worked in the building at least three days a week. In some cases, multiple office locations from a single company participated in the study. In each building, between seven and 19 (median 10) office workers from the participating company participated in the study. The participating office workers hosted environmental sensor packages at or near their desks, answered survey questions in a custom smartphone app, and wore wristband activity trackers for the one-year duration of the study. The study protocol was reviewed and approved by the Institutional Review Board at the Harvard T.H. Chan School of Public Health and individual participants provided informed consent before joining the study.

Building Assessment

Information about the office buildings in the Global CogFx Study was acquired through an online survey or by email correspondence that was completed by a representative from each participating company. Representatives from all buildings provided information including but not limited to the number of people in the building during operating hours, typical operating hours, building certifications, cleaning practices, and ventilation and filtration practices.

Indoor Environmental Assessment

In each of the 43 buildings, between one and 30 (median five) environmental sensor packages were deployed at or near participating office workers’ workstations. Across the 43 participating office buildings, seven different environmental sensor packages were used: the Harvard Healthy Buildings Sensor (a custom sensor package built for the Global CogFx Study at the Harvard T.H. Chan School of Public Health), the Tsinghua IBEM Sensor (a custom sensor package built at Tsinghua University[74]), the Awair Omni (Awair, Inc., San Francisco, USA), the ChemiSense CS-001 Indoor Air Quality Monitor (ChemiSense Inc., Berkeley, USA), the Tongdy MSD-16 Sensor (Tongdy Sensing Technology Corporation, Beijing, China), the Obotrons Indoor Air Quality Monitor (Obotrons Corporation Limited, Bangkok, Thailand), and the Yanzi Comfort (Yanzi Networks AB, Kista, Sweden). These environmental sensor packages all measured air temperature, RH, and carbon dioxide (CO_2) concentration at approximately one- to ten-minute intervals. Their reported temperature measurement accuracies ranged from ±0.2 C to ±1 C and resolutions ranged from 0.001 C to 0.1 C. Their reported RH measurement accuracies ranged from ±2% RH to ±5% RH and resolutions ranged from 0.01% RH to 1% RH. Raw RH measurements less than 2% RH and greater than 98% RH (approximately 2% of the raw RH measurements) were removed from the dataset before analysis. Measured CO_2 concentrations were used to estimate average building air exchange rates (AERs) during assumed ventilation system operating hours for each three-month period (December – February, March – May, June – August, and September – November), as described in the Indoor Environmental Assessment section in Chapter 2.

Outdoor Environmental Data

Outdoor temperature and RH data for the airport weather station located closest to each of the 43 buildings were obtained from The Weather Company's API Platform (https://weather.com). The distances between participating buildings and the closest airport weather stations ranged from 1.4 kilometers (km) to 49.5 km (median 12.1 km). Outdoor temperature data were used to calculate heating degree days (HDDs) and cooling degree days (CDDs) using a baseline of 65 F. For each building, mean daily HDDs and CDDs for each month were calculated by summing the total HDDs or CDDs in the month and then by dividing by the number of days.

Participant Surveys

At the beginning of study participation, office worker participants downloaded a custom smartphone app through which they were able to answer surveys and tests throughout the study. New surveys and tests were only sent to participants' smartphone apps when participants were at their workplaces, based on geofencing. When participants joined the study, a baseline survey was sent to their smartphone app for them to complete. Information obtained in the baseline survey included age, gender, workstation type, number of other people in their work room, job type, salary range, level of education, other demographic information, and job satisfaction information.

This analysis used data from two different symptom surveys that were both sent to participants' smartphone apps multiple times throughout their year of participation either at pre-scheduled times or when indoor environmental sensor packages measured specific preset threshold values for temperature, RH, or particulate matter with an aerodynamic diameter of 2.5 microns or less ($PM_{2.5}$). These thresholds were designed to ensure that a wide range of environmental conditions would be captured as exposures while participants were responding to the surveys. Each of the two surveys asked participants to select any symptoms they were currently experiencing from a list of symptoms. Survey 1 included the following symptoms: sore or dry throat; dry or itchy skin; dry, itching, or irritated eyes; stuffy or runny nose or sinus congestion; unusual tiredness, fatigue, or drowsiness; difficulty remembering things or concentrating; tension, irritability, or nervousness; and feeling depressed. Survey 2 included the following symptoms: burning or irritated eyes; sore throat; nasal congestion; headaches; migraines; frequent cough; wheezing; multiple colds; shortness of breath; sinus infections; hoarse voice; and sneezing attacks. Participants were able to select one, multiple, or none of the symptoms to indicate their current experience.

Descriptive Analysis

To evaluate how RH in office buildings varied across the year and across regions and to evaluate whether office buildings typically maintained intermediate RH levels (i.e. 40%-60%), descriptive analyses of indoor RH data were performed. Distribution plots were used to compare hourly device average indoor RH values during the assumed work hours of 9:00 – 17:00 on weekdays across the year in the four study regions: China/Thailand, India, the UK, and Mexico/USA. Data from Thailand and Mexico were grouped regionally with China and the USA, respectively, due to small sample sizes of one building each in Thailand and Mexico.

Statistical Analysis – Predictors of RH in Buildings

To evaluate the associations between building features and indoor RH, we used a generalized additive mixed model.[79] The outcome in the model was building hourly average indoor RH. Covariates in this model included building hourly average indoor temperature, quarterly AER, hourly average outdoor temperature, hourly average outdoor RH, hour of day, region, and building ventilation type. The indoor and outdoor temperature, outdoor RH, hour of day, and quarterly AERs were mean centered prior to modeling. The model also included a spline on day of year with two degrees of freedom (chosen after reviewing the shape of a penalized regression spline) and a random intercept for building. The data used in this model included data from all countries between the assumed work hours of 9:00 and 17:00 on weekdays.

Statistical Analysis – Associations between RH and Symptoms

We used generalized additive mixed models with a logit link (i.e. additive mixed logistic regressions)[79] to evaluate the associations between indoor RH and the odds of experiencing each of the seven symptoms that were reported in at least 10% of completed surveys. The seven symptoms, which were each treated individually as the model outcome, included: dry, itching, burning, or irritated eyes; dry or itchy skin; sore or dry throat; unusual tiredness, fatigue, or drowsiness; headaches or migraines; stuffy or runny nose or nasal or sinus congestion; and difficulty remembering things or concentrating. Each symptom's model only used data from the survey or surveys that listed the symptom.

The main exposure of interest in the model, indoor RH, was calculated as the average of RH measurements from the sensor closest to the participant during the hour prior to the time when the participant started the symptom survey. Both linear and spline terms for indoor RH were considered; in the end, a linear term was selected because the relationship between individual symptoms and indoor RH over the range of RH in the dataset appeared to be roughly linear on the logit scale. Other covariates in the model included mean indoor temperature from the sensor closest to the participant during the hour prior to the symptom survey, participant gender (male or female), country, and a spline on day of year with two degrees of freedom (chosen after reviewing the shapes of penalized regression splines). In cases where indoor RH or temperature measurements were not available from the sensor closest to the participant during the hour prior to the symptom survey, indoor RH or temperature was instead represented by the average of measurements from all other sensors in the building that made measurements during the hour before the participant completed the symptom survey. The models also included an interaction between participant gender and indoor RH to allow the impact of RH on the odds of experiencing a symptom to differ between males and females. Finally, the models included random intercepts for building and for participant. Models were also run with an additional covariate representing the number of other people who typically worked in the room where the respondent's workstation was located, but this covariate was not included in final models because its inclusion slightly decreased the models' adjusted R^2 values and model effect estimates were essentially unchanged.

The data used in these models were restricted to data from participants who answered at least one symptom survey during their year of participation and who answered the baseline survey at the start of the study. Further, survey responses were eliminated if there were no temperature or RH measurements made by any sensors in the building during the hour prior to the symptom survey being administered. Finally, only data from India, the UK, and the USA were included in the symptom modeling due to few symptom survey responses from the other three countries. After these restrictions, a total of 1,263 responses to both surveys submitted by 227 individual participants were used in the analysis (including 240 surveys submitted by 55 individuals from India, 266 surveys submitted by 40 individuals from the UK, and 757 surveys submitted by 132 individuals from the USA). For Survey 1, Survey 2, and for the combined data from the two surveys, the number of survey respondents per building ranged from one to ten with a median of seven. For Survey 1, the number of responses per person ranged from one to seven with a median of three. For Survey 2, the number of responses per person ranged from one to nine with a median of three. For Survey 1 and Survey 2 combined, the number of responses per person ranged from one to sixteen with a median of six.

All statistical modeling was performed using R version 3.6.2. Statistical significance for model results was evaluated at α=0.05 and suggestive evidence was evaluated at α =0.10.

Results

Building Characteristics

The characteristics of the 43 buildings in this study are presented by region in Table 3.1. The number of buildings in each region ranged from six buildings in the UK to 18 buildings in Mexico/USA. In all regions, the majority of buildings in the study reported using only mechanical ventilation. Indoor temperatures tended to be lower in Mexico/USA buildings compared to buildings in other regions and indoor RH tended to be lower in buildings in the UK and Mexico/USA compared to China/Thailand and India. UK buildings showed the smallest variation in both indoor temperature and indoor RH.

Table 3.1: Characteristics of buildings in the Global CogFx Study, by region.

	China/Thailand (n = 9) Median [Range] or n (%)	**India (n = 10) Median [Range] or n (%)**	**UK (n = 6) Median [Range] or n (%)**	**Mexico/USA (n = 18) Median [Range] or n (%)**
Ventilation Type				
Natural	0 (0%)	1 (10%)	0 (0%)	0 (0%)
Mixed-mode	3 (33%)	3 (30%)	0 (0%)	3 (17%)
Mechanical	6 (67%)	6 (60%)	6 (100%)	15 (83%)
Green Building Certification				
No	1 (11%)	7 (70%)	2 (33%)	6 (33%)
Yes	8 (89%)	3 (30%)	4 (67%)	12 (67%)
Healthy Building Certification				
No	8 (89%)	10 (100%)	6 (100%)	9 (50%)
Yes	1 (11%)	0 (0%)	0 (0%)	9 (50%)
Quarterly AER (hour^{-1}) [a]	1.15 [0.21, 2.34]	0.43 [0.15, 1.03]	0.52 [0.38, 1.29]	0.46 [0.19, 3.45]
Indoor temperature (C) during work hours [b]	25.7 [24.3 – 27.7]	26.1 [24.8 – 26.9]	25.3 [25.1 – 25.7]	23.8 [22.0 – 25.2]
Indoor RH (%) during work hours [b]	50.3 [40.2, 62.7]	44.5 [36.0, 51.8]	35.5 [31.3, 36.3]	37.4 [27.3, 54.7]
Outdoor temperature (C) during work hours [b]	20.7 [17.6 – 30.4]	27.5 [24.7 – 31.2]	15.3 [14.0 – 17.2]	12.4 [5.3 – 22.2]
Outdoor RH (%) during work hours [b]	71.8 [65.6 – 80.9]	51.1 [45.8 – 64.9]	66.7 [58.7 – 70.3]	75.2 [46.4 – 82.6]

[a] Displayed statistics for quarterly AER are the medians and ranges of average building AER across all three-month quarters for all buildings in each region.

[b] Displayed statistics for continuous temperature and RH variables are the medians and ranges of building means calculated between 9:00 and 17:00 on weekdays for each building in each region.

Descriptive Analysis of RH across Regions and Across the Year

Overall, low indoor RH measurements during assumed work hours were more common in Mexico/USA and the UK than in China/Thailand and India (Table 3.2, Figure 3.1). Hourly device average indoor RH levels during assumed work hours across the year were less than 40% RH 21% of the time in China/Thailand buildings, 31% of the time in India buildings, 45% of the time in Mexico/USA buildings, and 72% of the time in the UK buildings. On the other hand, hourly device average indoor RH levels during assumed work hours across the year exceeded 60% RH 25% of the time in China/Thailand buildings, 10% of the time in India buildings, 1% of the time in Mexico/USA buildings, and 1% of the time in the UK buildings. This left 54%-59% of indoor hourly device average RH values during assumed work hours to fall between 40% and

60% RH in China/Thailand, India, and Mexico/USA, while only 27% of indoor RH values fell between 40% and 60% RH in the UK.

Table 3.2: Summary statistics for hourly device average indoor RH measurements on weekdays between 9:00 and 17:00 by ventilation type, month, and region.

			Indoor RH (%)					
Region	**Month**	**Ventilation Type**	**Minimum**	**25th %ile**	**Median**	**Mean**	**75th %ile**	**Maximum**
China/ Thailand	Dec-Feb	*All*	*3.9*	*35.8*	*45.4*	*45.9*	*55.5*	*97.9*
		Mechanical	18.5	43.5	50.5	51.5	60.0	94.0
		Mixed-Mode or Natural	3.9	28.4	35.4	36.0	42.1	97.9
	Mar-May	*All*	*2.0*	*38.5*	*54.1*	*51.8*	*64.7*	*98.0*
		Mechanical	26.5	54.4	61.6	61.7	70.0	98.0
		Mixed-Mode or Natural	2.0	28.1	37.4	39.1	48.4	97.9
	Jun-Aug	*All*	*11.7*	*49.0*	*54.7*	*56.2*	*61.0*	*98.0*
		Mechanical	27.3	50.8	56.6	59.2	64.2	98.0
		Mixed-Mode or Natural	11.7	45.7	51.8	50.8	56.6	98.0
	Sep-Nov	*All*	*5.8*	*43.6*	*51.5*	*50.9*	*58.1*	*97.6*
		Mechanical	22.9	48.2	54.6	54.6	60.5	97.6
		Mixed-Mode or Natural	5.8	35.5	43.8	43.6	50.9	97.6
India	Dec-Feb	*All*	*12.0*	*36.2*	*41.2*	*43.3*	*48.4*	*75.3*
		Mechanical	12.0	34.0	38.0	37.7	42.0	59.8
		Mixed-Mode or Natural	24.8	39.1	45.5	47.8	56.8	75.3
	Mar-May	*All*	*18.5*	*37.1*	*41.8*	*42.0*	*46.3*	*75.0*
		Mechanical	18.5	38.7	42.8	42.7	46.7	75.0
		Mixed-Mode or Natural	25.5	35.6	39.9	41.1	45.1	72.6
	Jun-Aug	*All*	*28.7*	*45.7*	*49.7*	*50.1*	*54.3*	*98.0*
		Mechanical	35.4	46.3	49.6	50.3	53.9	98.0
		Mixed-Mode or Natural	28.7	44.7	49.8	49.9	55.1	73.1
	Sep-Nov	*All*	*24.3*	*44.3*	*51.4*	*52.1*	*60.4*	*79.5*
		Mechanical	24.3	39.0	45.2	45.2	50.0	69.2
		Mixed-Mode or Natural	28.7	49.9	57.7	56.9	64.2	79.5
Mexico/ USA	Dec-Feb	*All*	*3.6*	*22.4*	*28.1*	*31.4*	*38.8*	*72.4*
		Mechanical	11.4	21.6	26.5	29.5	34.0	71.4
		Mixed-Mode or Natural	3.6	30.2	38.0	38.6	46.4	72.4
	Mar-May	*All*	*6.0*	*27.4*	*36.6*	*36.4*	*45.0*	*72.7*
		Mechanical	6.0	27.0	36.0	36.1	45.7	72.7
		Mixed-Mode or Natural	8.0	34.1	39.5	38.3	42.6	68.8
	Jun-Aug	*All*	*23.8*	*44.0*	*48.0*	*47.3*	*51.1*	*76.0*
		Mechanical	23.8	43.5	47.8	47.0	50.8	76.0
		Mixed-Mode or Natural	26.0	47.3	51.1	50.4	54.6	71.0
	Sep-Nov	*All*	*3.4*	*35.0*	*42.7*	*41.5*	*49.0*	*68.4*
		Mechanical	6.2	35.2	42.5	41.3	48.7	68.4
		Mixed-Mode or Natural	3.4	33.0	44.9	42.8	53.2	67.2
UK	Dec-Feb	*All/Mechanical*	*6.7*	*27.7*	*31.8*	*30.7*	*35.5*	*92.0*
	Mar-May	*All/Mechanical*	*2.0*	*28.5*	*32.6*	*32.9*	*37.1*	*55.7*
	Jun-Aug	*All/Mechanical*	*14.8*	*37.5*	*42.8*	*42.9*	*48.2*	*97.0*
	Sep-Nov	*All/Mechanical*	*12.3*	*25.7*	*29.7*	*30.0*	*34.8*	*48.5*

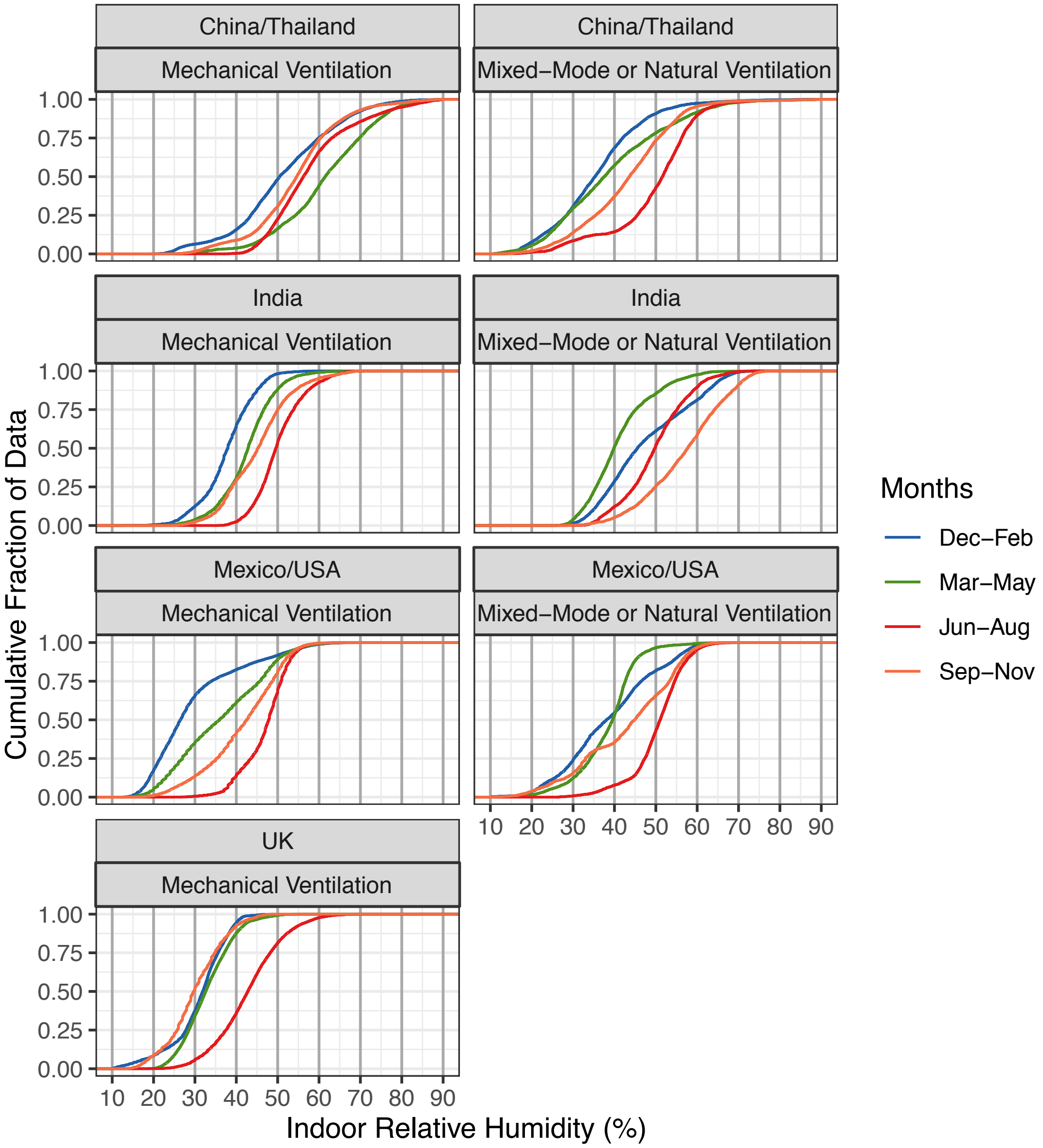

Figure 3.1: Cumulative distribution functions of hourly device average indoor RH measurements on weekdays between 9:00 and 17:00 by ventilation type, month of year, and region in the buildings in the Global CogFx Study.

During the study period, indoor RH during work hours tended to be low (i.e. <40% RH) in each region in the months of December – February (Figure 3.1). In buildings with all types of ventilation in China/Thailand, Mexico/USA, and the UK, more than half of each region's indoor RH values were outside the range of 40%-60% RH during December – February. Of the four regions, indoor RH was lowest in December-February in the UK, when 94% of measurements were less than 40% RH. On the other hand, indoor RH was most often moderate (i.e. 40%-60% RH) in June – August in all regions (Figure 3.1). Of the four regions, indoor RH was most consistently between 40% and 60% RH in June – August in India and Mexico/USA, where 84-85% of measurements were between 40% and 60% RH. Cumulative distributions functions separated by daily HDDs and CDDs, rather than by month of year, are presented in Appendix B; these functions support the observations made about Figure 3.1 and indicate that indoor RH during work hours tended to be lower (i.e. <40% RH) when heating conditions dominated and was most often moderate (i.e. 40%-60% RH) during months when cooling conditions dominated in China/Thailand and India and when neither cooling nor heating conditions dominated in Mexico/USA and the UK.

Effects of Building on Humidity

The results of the generalized additive mixed model analysis (Table 3.3) also demonstrate that indoor RH varied across the year and by region, after controlling for the other variables in the model, with the spline on day of year and the coefficients for the region variable indicating that the highest indoor RH measurements occurred in the middle of the year and in more tropical regions. Additionally, indoor RH was highest in the morning and tended to decrease throughout the workday. Indoor environmental quality metrics included in the model, temperature and AER, also were associated with indoor RH after controlling for the other variables in the model. As quarterly AER increased, indoor RH increased, possibly due in part to restriction of outdoor air relative to recirculated air by economizers combined with dehumidification by air conditioning during warmer months and reduced RH due to heating in cooler months. As indoor temperature increased, indoor RH decreased, possibly because the vapor pressure of water increases with temperature, so the RH in a parcel of air drops if that parcel of air is heated without the addition or removal of any water. Building ventilation type did not have a significant effect on indoor RH after controlling for other variables in the model. Model diagnostics suggested that multicollinearity between outdoor RH and indoor and outdoor temperatures was not present.

Table 3.3: Results from a generalized additive mixed model predicting indoor building average hourly RH (%) on weekdays between 9:00 and 17:00, with a spline on day of year and a random intercept for building.

	Effect estimate (95% CI)	***p*-value**
Ventilation (reference = Natural or Mixed-Mode)		
Mechanical	1.01 (-2.44, 4.46)	0.57
Region (reference = China/Thailand)		
India	-4.95 (-9.12, -0.78)	0.02
Mexico/USA	-5.81 (-9.55, -2.06)	0.002
UK	-8.84 (-13.75, -3.94)	0.0004
Indoor Temperature (C)	-1.11 (-1.15, -1.08)	<0.0001
Quarterly AER (hour^{-1})	1.31 (1.21, 1.41)	<0.0001
Outdoor Temperature (C)	0.86 (0.85, 0.87)	<0.0001
Outdoor RH (%)	0.22 (0.22, 0.22)	<0.0001
Hour of Day	-0.20 (-0.22, -0.18)	<0.0001
Adjusted R^2	*0.68*	

Characteristics of Survey Respondents

Descriptive data about the symptom survey are shown in Table 3.4. Over half (58-59%) of the survey respondents were from the USA. Respondents were generally well educated, with 44% of respondents reporting holding a doctorate degree while only 5-6% of respondents reported high school or some college as their highest level of education completed. Respondents were split evenly between the two genders. Most respondents worked in open office spaces without partitions and very few (approximately 5%) had private offices.

Table 3.4: Characteristics of individuals included in this analysis.

	Median [Range] or n (%)		
	Survey 1 Respondents (n = 211)	**Survey 2 Respondents (n = 215)**	**Survey 1 + Survey 2 Respondents (n = 227)**
Gender			
Male	104 (49%)	112 (52%)	116 (51%)
Female	107 (51%)	103 (48%)	111 (49%)
Country			
India	49 (23%)	50 (23%)	55 (24%)
UK	37 (18%)	39 (18%)	40 (18%)
USA	125 (59%)	126 (59%)	132 (58%)
Workstation Type			
Open space w/o partitions	141 (67%)	142 (66%)	151 (67%)
Open space w/ partitions	57 (27%)	60 (28%)	63 (28%)
Shared or single-person private office	11 (5.2%)	11 (5.1%)	11 (4.8%)
Other	2 (0.95%)	2 (0.93%)	2 (0.88%)
Highest Level of Education Completed			
Doctorate	93 (44%)	95 (44%)	101 (44%)
Master's degree	3 (1.4%)	3 (1.4%)	3 (1.3%)
Professional degree	42 (20%)	43 (20%)	45 (20%)
4-year degree	57 (27%)	58 (27%)	61 (27%)
2-year degree	4 (1.9%)	5 (2.3%)	6 (2.6%)
Some college	8 (3.8%)	7 (3.3%)	8 (3.5%)
High school	4 (1.9%)	4 (1.9%)	4 (1.8%)
Age	32 [21 – 61]	32 [21 – 62]	32 [21 – 62]
# people working in room in which respondent's workstation is located	40 [0 – 265]	40 [0 – 265]	40 [0 – 265]

Effect of Humidity on Symptoms

The seven symptoms in this analysis can be put into three groups that have previously been used by other researchers:[113–115] dry or itchy skin; mucous membrane symptoms (dry, itching, burning, or irritated eyes; sore or dry throat; and stuffy/runny nose or nasal/sinus congestion); and central nervous system (CNS) symptoms (unusual tiredness, fatigue, or drowsiness; headaches or migraines; and difficulty remembering things or concentrating). The number of surveys in which participants reported each symptom are shown in Table 3.5. Each of the seven symptoms was reported in at least 10% of surveys. The most prevalent of these symptoms, unusual tiredness, fatigue, or drowsiness, was reported in 17% of responses to Survey 1. The least common of these symptoms were sore or dry throat and dry, itching, burning, or irritated eyes, each of which was reported in 10% of responses to Surveys 1 and 2. Female participants reported a larger percentage of each of the seven symptoms than male participants did (Table 3.5) even though there were approximately equal numbers of male and female respondents to the surveys (Table 3.4). The largest gender discrepancy occurred for dry, itching, burning, or irritated eyes; for this symptom, 65% of the symptom reports came from females.

Table 3.5: Numbers and percentages of completed surveys in which each symptom was reported.

		Completed Surveys Reporting Symptom			**Completed Surveys**
		Females	**Males**	**Total**	
Symptom	**Survey**	**n (% of Total Completed Surveys Reporting Symptom)**		**n (% of Completed Surveys)**	**n**
Central Nervous System Symptoms					
Unusual tiredness, fatigue, or drowsiness	1	51 (53%)	45 (47%)	96 (17%)	577
Headaches or migraines	2	54 (55%)	44 (45%)	98 (14%)	686
Difficulty remembering things or concentrating	1	50 (63%)	29 (37%)	79 (14%)	577
Mucous Membrane Symptoms					
Dry, itching, burning, or irritated eyes	1 & 2	81 (65%)	43 (35%)	124 (10%)	1263
Sore or dry throat	1 & 2	66 (55%)	54 (45%)	120 (10%)	1263
Stuffy/runny nose or nasal/sinus congestion	1 & 2	113 (55%)	94 (45%)	207 (16%)	1263
Dry or itchy skin	1	53 (64%)	30 (36%)	83 (14%)	577

Results of the generalized additive mixed models to evaluate associations between indoor RH and individual symptoms, controlling for indoor temperature, gender, country, and day of year, are shown in Table 3.6. For Surveys 1 and 2, the indoor RH levels experienced by participants in the hour before the survey ranged from 14% to 70% RH (second percentile 19% RH, ninety-eighth percentile 60% RH). For both males and females, higher average indoor RH in the hour before the survey was suggestively or significantly associated with lower adjusted odds of reporting dry or itchy skin. A ten percentage point increase in RH across low and intermediate RH values was associated with a 54% reduction (OR 0.46, 95% confidence interval [CI]: 0.29, 0.75, p=0.002) among females and a 42% reduction (OR 0.58, 95% CI: 0.33, 1.02, p=0.06) among males in the adjusted odds of reporting dry or itchy skin. Among females only, higher average indoor RH in the hour before the survey was suggestively or significantly associated with lower adjusted odds of reporting two mucous membrane symptoms. Among females, a ten percentage point increase in RH across low and intermediate RH values was associated with a 26% reduction in the adjusted odds of reporting dry, itching, burning, or irritated eyes (OR 0.74, 95% CI: 0.52, 1.06, *p*=0.099), and with a 40% reduction in the adjusted odds of reporting a sore or dry throat (OR 0.60, 95% CI: 0.42, 0.86, *p*=0.005). Among males only, higher average indoor RH in the hour before the survey was significantly associated with lower adjusted odds of reporting one CNS symptom: a ten percentage point increase in RH across low and intermediate RH values was associated with a 42% reduction in the adjusted odds of reporting unusual tiredness, fatigue, or drowsiness (OR 0.58, 95% CI: 0.36, 0.95, *p*=0.03).

Indoor RH was not significantly or suggestively associated with the adjusted odds of reporting dry, itching, burning, or irritated eyes among males (*p*=0.59); sore or dry throat among males (*p*=0.31); unusual tiredness, fatigue, or drowsiness among females (*p*=0.70); headaches or migraines among females (*p*=0.39) or males (*p*=0.18); stuffy or runny nose or nasal or sinus congestion among females (*p*=0.25) or males (*p*=0.89); or difficulty remembering things or concentrating among females (*p*=0.87) or males (*p*=0.36). However, the point estimates of the adjusted odds ratios of females and males reporting each of these symptoms as RH increased were all less than one.

For the three mucous membrane symptoms and for dry or itchy skin, the adjusted odds of reporting symptoms were lower, though not significantly so, among males than among females, after controlling for indoor RH, indoor temperature, country, and day of year. Conversely, the adjusted odds of reporting the three CNS symptoms were higher, though not significantly so, among males than females. There were also some noticeable differences between countries, with the odds of reporting any symptom in India being lower than in the USA (only significantly so for stuffy or runny nose or nasal or sinus congestion), after controlling for indoor RH, indoor temperature, gender, and day of year.

Table 3.6: Results from generalized additive mixed models evaluating whether indoor RH was associated with the log-odds of reporting each symptom. In addition to the variables in the table, the models also included a spline for day of year with two degrees of freedom and random intercepts for building and participant. ORs per 1% RH and 1 C.

	Mucous Membrane Symptoms			**Central Nervous System Symptoms**			
	Dry, itching, burning, or irritated eyes	**Sore or dry throat**	**Stuffy/runny nose or nasal/sinus congestion**	**Unusual tiredness, fatigue, or drowsiness**	**Headaches or migraines**	**Difficulty remembering things or concentrating**	**Dry or itchy skin**
	Surveys 1 & 2	**Surveys 1 & 2**	**Surveys 1 & 2**	**Survey 1**	**Survey 2**	**Survey 1**	**Survey 1**
	OR (95% CI)	**OR (95% CI)**	**OR (95% CI)**	**OR (95% CI)**	**OR (95% CI)**	**OR (95% CI)**	**OR (95% CI)**
RH_{in} (%)	0.97 (0.94, 1.01)*	0.95 (0.92, 0.99)***	0.98 (0.95, 1.01)	0.99 (0.95, 1.04)	0.98 (0.95, 1.02)	1.00 (0.95, 1.04)	0.93 (0.88, 0.97)***
$Temp_{in}$ (C)	0.91 (0.78, 1.06)	1.09 (0.95, 1.25)	1.02 (0.90, 1.16)	1.11 (0.93, 1.33)	0.98 (0.84, 1.14)	1.12 (0.92, 1.37)	1.09 (0.89, 1.33)
Gender (Reference = Female)							
Male	0.21 (0.03, 1.39)	0.23 (0.04, 1.30)*	0.42 (0.09, 1.91)	4.82 (0.52, 44.5)	1.05 (0.19, 5.75)	1.17 (0.08, 16.3)	0.23 (0.02, 2.75)
Country (Reference = USA)							
UK	1.46 (0.66, 3.21)	0.83 (0.40, 1.74)	0.56 (0.28, 1.11)	1.47 (0.70, 3.11)	0.87 (0.43, 1.78)	1.83 (0.78, 4.34)	1.28 (0.57, 2.86)
India	0.68 (0.24, 1.94)	0.86 (0.36, 2.03)	0.25 (0.10, 0.59)***	0.71 (0.25, 1.96)	0.86 (0.37, 2.01)	0.93 (0.30, 2.86)	0.66 (0.20, 2.20)
RH x Gender (Reference = Female)							
RHxMale	1.02 (0.97, 1.07)	1.03 (0.99, 1.08)	1.02 (0.98, 1.06)	0.96 (0.90, 1.01)	0.99 (0.95, 1.03)	0.98 (0.91, 1.04)	1.02 (0.96, 1.09)

$^{*}p<0.10$
$^{**}p<0.05$
$^{***}p<0.01$
CI: confidence interval
OR: odds ratio
RH_{in}: indoor relative humidity
$Temp_{in}$: indoor temperature

Discussion

The indoor RH levels we observed in office buildings in six countries were often outside of the range of 40%-60% RH where threats of viruses, mold, and dust mites are expected to be minimized and where host susceptibility to respiratory viruses is least compromised. In the most extreme instances measured in this study, only 6-7% of hourly device average indoor RH values measured during assumed work hours in UK buildings in December – February and September – November were between 40% and 60% RH, while the remaining 93-94% of RH values were lower than 40% RH. In addition to enhancing threats from viruses and other indoor contaminants, our results suggest that low indoor RH levels are problematic because they lead to increased reports of dry or itchy skin, mucous membrane symptoms (females only), and a CNS symptom (males only). These symptom-RH relationships were linear across the full range of measured RH values in one year of data from three countries (i.e. 14%-70% RH). Based on our modeling of RH and symptom data, increasing RH from 31.8% RH (median RH in UK buildings during assumed work hours in December – February) to 40% RH would result in a 36% reduction (95% CI: -60%, +2%) among males and a 47% (95% CI: -64%, -21%) reduction among females in the adjusted odds of reporting dry or itchy skin; a 22% (95% CI: -42%, +5%) reduction among females in the adjusted odds of reporting dry, itching, burning, or irritated eyes; a 34% (95% CI: -51%, -12%) reduction among females in the adjusted odds of reporting sore or dry throat; and a 36% (95% CI: -57%, -4%) reduction among males in the adjusted odds of reporting unusual tiredness, fatigue, or drowsiness.

Comparison with Prior Research on Indoor Environment and Symptoms

Our results are consistent with prior analyses of RH and symptoms and build upon prior work by evaluating RH as a continuous variable rather than only comparing a limited number of RH levels and by accounting for effect modification by gender. One study in a Finnish office building found that a one percentage point increase in indoor RH was associated with significantly reduced odds of skin dryness (OR 0.96, 95% CI: 0.93, 0.99), skin rash (OR 0.94, 95% CI: 0.88, 1.00), and nasal dryness (OR 0.94, 95% CI: 0.91, 0.97) controlling for temperature.[49] Though not significant, an increase in indoor RH was also associated with reduced odds of eye dryness, pharyngeal dryness, nasal congestion, and nasal excretion.[49] Of note, this study did not account for any personal factors in the modeling, and in fact did not report on demographics of the study population. Gender was an important effect modifier in our analysis and it's possible that the odds ratios for additional symptoms in the Finnish study would have been significant among females or males if gender had been considered. In addition, this prior study also used a limited range of temperatures (21.5-23.7 C) and RH values (20.0%-41.2%), so it is possible they failed to see significant effects of indoor RH on reports of eye dryness or throat dryness, as we saw among females, due to the small range of exposures studied. Another study in a Japanese office building found that decreasing RH across a larger range of 25%-60% RH was significantly associated with increased eye irritation, sore or irritated throat, and skin dryness (no other symptoms evaluated), though this analysis also did not consider gender or any other personal or building characteristics.[48] Our analysis builds on the Finnish and Japanese office building results, and other prior work, by demonstrating that the association between indoor RH and the odds of office workers reporting some symptoms exists across multiple regions with varied indoor RH levels and that gender also impacts the association between RH and symptom reports. Moreover, our analysis fills a gap demonstrated by the Finnish office building study and called out in a recent review of impacts of low indoor RH levels on human health:[46] most existing studies compare effects of a small number of distinct RH levels or over a small range of RH levels, and the resulting poor resolution between experimental humidity levels makes it difficult to determine what levels of indoor RH are acceptable. Our modeling suggests that there is a linear relationship between indoor RH and the odds of reporting some symptoms across the full range of realistic RH levels in office buildings. As a result, our work indicates that there is no clear threshold for acceptable indoor RH; rather, building managers can expect consistently fewer symptom reports as RH increases across normal levels.

There is also a body of literature linking indoor temperature and symptoms in buildings.[111,116] One large analysis used data from 95 buildings in the USA-based Building Assessment Survey and Evaluation (BASE) Study to explore the relationship between indoor temperature and humidity measured during one workday and symptoms recalled over the past four weeks.[27] This study found that increased mean building temperature (ranging from 21.6 C to 24.8 C) but not humidity ratio (a mass-based measure of absolute humidity calculated from measured RH ranging from 9.4% to 62.4%) was significantly associated with increased odds of reporting cough and dry or irritated eyes after adjusting for season, gender, smoking, asthma diagnosis (for cough), HDDs, and CDDs. At first glance, these findings seem to be in conflict with our finding that RH but not temperature was significantly or suggestively associated with reduced odds of three symptoms among females and two symptoms among males. However, it is possible that the lack of significant association between humidity and symptoms in the BASE analysis was because they did not account for effect modification by gender (simply controlling for gender in the model, as they did, would not suffice to account for effect modification by gender which was observed in our analysis) or by concurrently evaluating the effects of temperature and absolute humidity (rather than RH), which are expected to be collinear because high absolute humidity levels are only achievable at high temperatures.[41]

RH and Symptoms in Office Workers

Our finding of significant or suggestive evidence of associations between indoor RH and two of three mucous membrane symptoms in females but not in males could be due to females' increased sensitivity to symptoms. At low RH, symptoms may result from mucous membrane drying. Tear film evaporation is faster, blink frequency also may be higher, and transepidermal water loss is enhanced at low RH.[46,109] Because the drying of the mucous membranes is not expected to differ by gender, it is possible that both genders in our study experienced this physiological drying, but that only females noticed it. This interpretation is supported by prior literature that indicates healthy females tend to report more symptoms than healthy males on a variety of symptom scales and measures.[111,112] In our study, males reported fewer instances of the seven symptoms evaluated (Table 3.5) and our model results show that males had non-significantly lower odds of reporting four of the seven symptoms compared to females, after adjusting for RH, indoor temperature, country, and day of year. If females' symptom reports represent the unnoticed and unreported experiences of males, as well as their own experiences, then our finding that females report more mucous membrane symptoms as RH decreases suggests that RH has an important impact on all office workers' physiology throughout their workday. If, on the other hand, males actually do not have a physiological mucous membrane response to low RH and correctly do not report increased mucous membrane symptoms as RH decreases, it is still important to consider the impact of low RH environments on comfort and health of female office workers who did report increased mucous membrane symptoms as RH decreased.

Strengths & Limitations

This work is limited by its reliance on self-report symptom data which may not represent actual physiological changes, and which are susceptible to being over- or under-reported. However, participants did not have any incentive to misrepresent their symptoms, as they were aware that their individual survey answers would not be shared with their employers. Importantly, the use of a smartphone app to ask about participants' current symptoms eliminated the issue of recall bias, which may be present in other studies of reported symptoms experienced over some period of time. This work is also limited by its reliance on volunteer knowledge worker participants in a convenience sample of office buildings, which may reduce the ability to generalize our results to the experience of all office workers in all buildings around the world. Nonetheless, this study did include data from 43 buildings in six countries and the year-long concurrent measurement of indoor environmental parameters and administration of symptom questionnaires is a significant advance over prior work that relied on symptom recall or that evaluated associations between non-concurrently measured indoor environmental parameters and symptoms. Furthermore, unlike prior work, we were able to consider additional temporal and personal variables in our modelling of the impact of indoor RH on symptoms and, in particular, to account for effect modification by gender.

Implications for Humidity in Office Buildings

In our data, it was more common for RH to be lower than 40% RH than to be higher than 60% RH (42% vs. 7% of hourly device average values during assumed work hours across all regions). Indoor dryness generally occurred during winter months and when heating conditions dominated, possibly because heating outdoor air for ventilation without any humidification reduces its RH. During December – February, 35%-94% of indoor RH values in each region were less than 40% RH. Even in June – August, 5%-36% of indoor RH values in each region were less than 40% RH.

Our results suggest that there is an opportunity to optimize RH in office buildings in all seasons and especially in colder or winter months to reduce viral transmission by droplets deposited on surfaces or by airborne aerosols. Even in the absence of reported symptoms, low RH can affect human immune defenses against viral pathogens.[106,107] Given the frequent low RH measurements seen in some study buildings, especially in wintertime, it seems that buildings have an opportunity to reduce the susceptibility of their occupants to respiratory viruses by increasing indoor RH. Such an adjustment would also affect viral viability, reducing viability for several common viruses including SARS-CoV-2.[42] Although office workers could still be infected by respiratory viruses outside of work, the chance of viral transmission in the office would be lower if RH was maintained at intermediate level, in addition to other adjustments like improving outdoor air ventilation, air filtration, and encouraging handwashing. In buildings with low RH where humidity cannot be adjusted, building managers could pay extra attention to alternative risk reduction strategies they are able to implement.

Air humidification may be one way to address low indoor RH values and to reduce occupant-reported symptoms, but humidity should not be increased too much. Viability of some enveloped viruses, including SARS-CoV-2,[42] may increase in aerosols and droplets if RH increases above 75-85%[39] and problems like mold and dust mites are more common when indoor RH exceeds 60-75% and 50%, respectively.[44,45,117] The American Society of Heating, Refrigerating and Air-Conditioning Engineers recommends that indoor humidity in occupied spaces be controlled to ensure a dew point of 15 C or lower;[24] at the median temperature during assumed work hours in USA buildings in our study (23.3 C), this recommendation corresponds to a maximum RH of 59%.

Our results suggest that humidity control should be explicitly considered, in addition to consideration of ventilation and temperature targets, when buildings retrofit their ventilation systems and when new buildings are constructed. Where outdoor air is often too humid, dedicated outdoor air systems can provide efficient dehumidification by decoupling humidity control from temperature control.[118] Where outdoor air is often too dry, variable air volume units with adiabatic humidification of outdoor air can provide efficient humidification of incoming outdoor air.[119] When adding humidification to a building, installing vapor barriers and insulating cold indoor surfaces can help protect against mold. Energy recovery devices, like enthalpy wheels, can also be useful for humidity control in buildings.

Conclusions

Our analysis demonstrates that measured RH in the 43 buildings in the Global CogFx Study was often outside the optimal 40%-60% RH zone where risks of viral transmission, dust mites, and mold are expected to be diminished and where human defenses against respiratory pathogens are expected to be unaffected. Some of the variables we found to be linked to low indoor RH include: located in northern latitudes, during winter, at the end of the workday, and when outdoor RH or temperature were low. Our analysis also demonstrates that low indoor RH may result in more dry or itchy skin among male and female office workers, more mucous membrane symptoms (dry, itching, burning, or irritated eyes and sore or dry throat) among female office workers, and more unusual tiredness, fatigue, or drowsiness among male office workers. These effects of RH were observed after controlling for relevant office characteristics including indoor temperature. The RH-symptom relationships in this study were observed to be linear across the range of RH measurements collected over one year in three countries and, across the low to moderate observed RH values, there did not appear to be a threshold RH above or below which the RH-symptom relationships plateaued. Humidification, ideally by a system that has separate humidity and temperature control, to maintain indoor RH between 40% and 60% may be considered as a way to reduce occupant symptoms and promote occupant comfort and health more broadly by contributing to reduced risk of transmission of respiratory viruses like SARS-CoV-2 and by reducing the likelihood of mold or dust mite problems.

CHAPTER 4: THE EFFECTS OF TEMPERATURE AND THERMAL COMFORT ON CREATIVITY AND INTUITIVE JUDGEMENT AMONG MALES AND FEMALES

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E.R.J conceptualized this analysis, developed the study methodology and analysis plan, carried out the study activities, performed the formal analysis, and prepared the manuscript. B.A.C. and J.D.S. provided input into the study design and methodology and provided critical revision of the manuscript. J.G.A. conceptualized this analysis, provided input into the study design and methodology, acquired financial support for this project, provided critical review of the manuscript, and supervised the project.

Abstract

Creativity and intuitive judgement are cognitive processes that are important for office workers' work performance. Though there is evidence that creativity can be influenced by physical attributes of a work environment and that intuitive judgement can be influenced by psychological states, little is known about how indoor temperature affects creativity or intuitive judgement in spite of the robust literature demonstrating effects of indoor temperature on other cognitive processes like attention, memory, reasoning, and mathematical processing. To address this gap, we exposed 78 young adults to temperatures ranging from 65.5 F to 78.6 F and, after an acclimatization period of at least 54 minutes, tested their divergent creativity (using the alternative uses test [AUT]), convergent creativity (using the compound remote associates test [cRAT]), and intuitive judgment (using a word triads intuitive judgement test). We examined associations between room temperature and performance on all three tests, as well as throughput on the cRAT and the intuitive judgement test. We also evaluated differences in the same set of outcomes between people who had high and low self-reported thermal comfort. In gender-stratified models adjusted for indoor relative humidity, baseline creative personality, and clothing, associations between indoor temperature and cRAT and AUT fluency, elaboration, flexibility, and originality scores were consistently positive (i.e. better creativity at higher temperatures), but did not reach statistical significance. In gender-stratified models adjusted for the same three variables, associations between indoor temperature and throughput on the cRAT and intuitive judgement test were consistently positive (i.e. slower time to correct response at higher temperatures), and approached statistical significance among females but not males. Furthermore, females reported lower thermal comfort than males when exposed to temperatures between 65.5 F and 70 F. Females who reported worse-than-neutral thermal comfort right before

outcome testing had significantly worse AUT fluency, elaboration, and flexibility scores (with suggestive evidence for worse AUT originality scores, as well) than females who reported neutral or better thermal comfort. Thermal comfort was not significantly associated with AUT scores among males or with cRAT, intuitive judgement, or throughput scores among males or females. These results suggest that warmer temperatures across the range of 65.5-78.6 F may promote divergent and convergent creativity and that thermal comfort, which is worse among females compared to males when room temperature is slightly cool, is important for divergent creativity. Consequently, buildings should account for gender-specific thermal preferences to fully maximize occupants' work performance.

Introduction

Environmental conditions inside office buildings can have non-negligible impacts on people's health, comfort, and performance at work. Temperature is one indoor environmental quality parameter that has been found to affect aspects of work performance including long-term memory,[51] working memory,[52] attention,[53,54] mathematical processing,[53–55] processing speed,[56] and reasoning.[57–59]

The effect of temperature on work performance has been measured using many different tests. For example, temperature has been found to impact accuracy and throughput on number calculation tests,[53–55,120] throughput on the Stroop color-word test with and without feedback,[53,54] throughput on a sustained attention task,[54] accuracy on a memory typing task,[51] and reaction time and accuracy on the n-back working memory test.[52] These impacts of temperature have been measured at levels that are commonly found in workplaces. Two meta-analyses of temperature and cognition indicate that worker performance is best when air temperature is between 70 F and

79.9 F,[28] with maximum performance around 71.6 F.[1] Outside of this range, cognition declines. Increasing room temperature from 71.6 F to 86.0 F is expected to be associated with an 8.9% reduction in work performance[1] and reducing room temperature from 65-75 F to 50-64.9 F is expected to be associated with a 7.81% reduction in work performance.[28] In addition to affecting work performance, deviations from neutral temperatures also lead to more reports of thermal discomfort, with females being more likely than males to report suboptimal thermal comfort in slightly cool conditions.[116,121] Thermal comfort can impact work performance, as well; office workers in thermally-comfortable environments have been shown to score 5.4% higher on tests of higher-order decision making ability.[23]

Although research on work performance has typically focused on memory, attention, mathematical processing, and reasoning as important skills for office workers, innovative or creative thinking is also important in work performance,[30,31] as is intuition which guides workers' thinking much of the time.[32] It is unclear whether the same conditions that promote traditional domains of worker productivity also promote creativity and intuitive judgement, particularly since creativity is not necessarily well correlated with other kinds of cognitive ability.[122] Like traditionally-studied aspects of work performance, creativity can also be impacted by physical attributes of workers' work environments such as disorder and the presence of windows or views.[123–126]

However, very limited research has examined whether indoor environmental quality parameters like temperature, rather than physical attributes of work environments, can impact worker creativity. Despite a robust literature demonstrating effects of temperature on other aspects of cognitive function and two studies demonstrating the effects of ventilation rate[72] and light[127] on creativity, only one study has evaluated the effect temperature on creativity[128] and this study is limited by its use of a single composite creativity score from one creativity test and by its short 25-minute acclimatization time, as it takes approximately one hour for the effect of pre-exposure conditions to disappear.[3] Similarly, no research has demonstrated the effect of any indoor environmental quality parameters, including temperature, on intuitive judgement, although it has been shown that intuitive judgement can be impacted by psychological states such as moods.[129] It is important to understand how temperature and thermal conditions affect creativity and intuitive judgement so diverse types of thinking can be accounted for when determining optimal conditions in an office building.

Our goal was to address these gaps by evaluating whether temperature affects two types of creativity, as well as intuitive judgement, in a convenience sample of 78 young adults exposed to temperatures between 65.5 F and 78.6 F in a laboratory setting. We evaluated associations between measured room temperature and convergent creativity, divergent creativity, intuitive judgement, and throughput on tests of convergent creativity and intuitive judgement after an acclimatization period of at least 54 minutes. To explore the effects of gender differences in thermal comfort, we also used gender-stratified analyses to test whether scores on tests of convergent creativity, divergent creativity, and intuitive judgement, as well as throughput on tests of convergent creativity and intuitive judgment, differed between individuals who reported worse-than-neutral thermal comfort and individuals who reported thermal comfort as neutral or better.

Materials & Methods

Study Design

This experiment took place in January – March 2020 in a temperature-controlled room where the room thermostat was set to one of four temperature conditions (68 F, 72 F, 76 F, or 82 F) that was randomly chosen each study day. The experiment consisted of a convenience sample of young adult participants each sitting in the temperature-controlled study room and completing creativity and intuitive judgement tests on a computer after at least 54 minutes of temperature exposure. The study protocol was approved by the Institutional Review Board at the Harvard T.H. Chan School of Public Health.

Study Location

The study took place at the Harvard Decision Science Lab in Cambridge, Massachusetts. Participants completed preliminary study activities in one of two waiting areas with unmanipulated environmental conditions before entering a small study room where they remained for the rest of the study (Table 4.1). The study room was 6.0 feet wide, 8.4 feet long, and 8.8 feet tall. The study room had a drab aesthetic and no windows, and was outfitted with two chairs with fabric padding and a small table. A laptop that participants used to complete study activities was on the table.

Table 4.1: Study protocol with medians and ranges of time spent in each location or study period.

Location	Period	Task	Purpose/What was Measured
Waiting area (median 12, range 8-26 min)	Set up	Complete consent form	--
		10 items from the preliminary IPIP scale measuring 'Creativity' AB5C facet	Baseline creative personality
		Oregon Vocational Interest Scale	Baseline interest in creative vocations
		Positive Affect and Negative Affect Schedule	Baseline mood
Temperature-controlled study room (median 95, range 84-113 min)	Acclimatization period (median 63, range 54-86 min)	Environmental questionnaire	Thermal comfort, etc. *after 0 minutes*
		Demographic questionnaire	Gender, age, etc.
		Big-Five Factor Markers Assessment	Personality
		Addition and subtraction test	Simulated office work
		0,1,2,3-back tests	Simulated office work
		Environmental questionnaire	Thermal comfort, etc. *after median 29, range 21-51 min*
		Stroop color-word test	Simulated office work
		Addition and subtraction test	Simulated office work
		Stroop color-word test	Simulated office work
		[Optional] 0,1,2,3-back tests	Simulated office work
		Environmental questionnaire	Thermal comfort, etc. *after median 59, range 51-81 min*
		Positive Affect and Negative Affect Schedule	Mood
	Outcome testing (median 31, range 24-39 min)	Intuitive Judgement Test	Intuitive judgement
		Alternative Uses Test	Divergent creativity
		Compound Remote Associates Test	Convergent creativity
		Titles Test	Divergent creativity
		Environmental questionnaire	Thermal comfort, etc. *after median 94, range 83-112 min*
Waiting area	Clean up	Review debriefing form	--

The study room was situated inside a larger facility with a large computer lab (across the hall from the study room), an entry area where people could register for studies (down the hall from the study room), four other small- to medium-sized office-like rooms similar to the study room (down the hall from the study room), and two single-occupant bathrooms (down the hall from the study room). For the duration of this study, these additional lab spaces were unoccupied most of the time, with the exception of two to three researchers for this study seated in the large computer lab and approximately one to four lab staff either in one of the small offices or in the entry area.

The lab had its own mechanical ventilation system which was not shared with other spaces in the building where the lab was located. The lab's outdoor air unit (Mitsubishi PURY-P192 controlled by a G50 centralized controller, Mitsubishi Electric Corporation, Japan) was located in a large mechanical room next to the lab and drew outdoor air from sidewalk-level intake grilles. The outdoor air unit was linked with an energy recovery ventilator (Venmar CES ERV1000i, Nortek Air Solutions, O'Fallon, MO, United States) located in the plenum space of the lab. The supply air from the energy recovery ventilator was ducted to multiple indoor heating and cooling units (Mitsubishi PEFY, Mitsubishi Electric Corporation, Japan) located in the plenum space throughout the lab. One of these indoor units was ducted directly to a diffuser in the ceiling of the study room. This unit was controlled by a thermostat on the wall of the study room (MA Remote Controller PAR-21MAA, Mitsubishi Electric Corporation, Japan). Air entered the study room from the diffuser in the ceiling and flowed out of the room into the adjacent hallway through the crack under the door. This configuration allowed the temperature in the study room to be changed independently from the rest of the facility when the study room door was closed.

During the study, ventilation operation was evaluated in two ways. To estimate outdoor air ventilation to the whole lab space, carbon dioxide (CO_2) was measured in supply and return air ducts at the energy recovery ventilator throughout the study using HOBO data loggers (model MX1102; Onset Computer Corporation, Bourne, MA, United States; accuracy ±50 ppm, range 0-5,000 ppm[130]). Airflow into the study room was measured at the ceiling diffuser using a balometer (Alnor EBT731-STA; TSI Incorporated, Shoreview, MN, United States) once each morning before any participants entered the study room.

Indoor Environmental Conditions

Air temperature in the study room was the only variable manipulated during the experiment. On the morning of each study day, one of four temperature targets (68 F, 72 F, 76 F, and 82 F) was selected randomly and entered into the in-room thermostat at least 1.5 hours before any participants entered the study room. Actual room temperatures deviated from these four thermostat setpoints (in-room temperature measurements described in more detail in the Exposure Measures: Temperature, Thermal Comfort, and Perceived Temperature section in this chapter), with substantial overlap between measured temperatures when the thermostat was set to 72 F and 76 F and with measured temperatures several degrees lower than the target temperature when the thermostat was set to 82 F. As a result of these deviations, measured study room temperatures, rather than thermostat setpoint temperatures, were used in study analyses. Only one participant took part in the study at a time and the thermostat was not reprogramed between participants. The thermostat fan speed was set at level three and the thermostat display screen was cleared while participants were in the study room.

Study Population

Study participants were recruited through the Harvard Decision Science Lab participant pool, a group of approximately 10,000 individuals who have completed a basic screening questionnaire and who are able to enroll in studies at the lab. Members of the participant pool were only eligible to register for this study if their age was at least 18 years and not more than 35 years and if they were native English speakers. Before registering for the study, potential participants were shown an additional list of exclusion criteria and were asked to not register any of the criteria applied to them. These additional exclusion criteria included: history of claustrophobia, schizophrenia, or panic attacks; history of chronic autoimmune or inflammatory disease; historical or current diagnosis of diabetes or thyroid disease; current pregnancy; current use of antibiotics, chemotherapy, prednisone, beta blockers, thyroid medication, or NSAIDS; current illness (e.g. flu); history of drug or alcohol abuse; and colorblindness. For this study, the final analytic population included all participants who consented to have their data used in the study, who adequately completed outcome assessments, and who self-reported gender as either male or female.

Study Protocol

Participant study activities are outlined in Table 4.1. Only one participant took part in the study at a time. When each participant arrived at the study location, they spent between eight and 26 minutes (median 12 minutes) in a waiting area where the conditions were not manipulated while being consented into the study and completing three questionnaires. The three questionnaires participants completed in the waiting area included: a creative personality assessment (consisting of the ten items that measure the creativity facet from the Preliminary International Personality Item Pool (IPIP) Scales Measuring the 45 Abridged Big Five-Dimensional Circumplex (AB5C) Facets[131,132]), an assessment measuring vocational interests including interest in creative vocations (the 92-item Oregon Vocational Interest Scale[122]), and a mood assessment (the Positive Affect and Negative Affect Schedule[133]).

After completing the waiting area tasks, each participant entered the temperature-controlled study room and was seated in a chair at a table with a laptop and an external mouse. The first portion of each study room session was an acclimatization period that lasted as long as it took participants to navigate through the designated questionnaires and tests, but we ensured this period lasted at least 54 minutes by assigning extra n-back tests to participants who completed the other activities in less than 54 minutes. Actual acclimatization periods of the analytic population ranged from 54 to 86 minutes (median 63 minutes). During the acclimatization period, participants completed an environmental questionnaire (presented three times during the acclimatization period and described in more detail in the Exposure Measures: Temperature, Thermal Comfort, and Perceived Temperature section in this chapter), a demographic questionnaire (that asked about age, gender, race, nationality, language competency, education, employment, overall physical and mental health, time of most recent food consumption, time of most recent caffeine consumption, time of most recent alcohol consumption, number of hours slept the previous night, and recent physical activity), a personality scale (the 50-item IPIP version of the Big-Five Factor Markers Assessment[134,135]), a series of traditional productivity tests to simulate office work (including two-digit addition and subtraction tests, Stroop color-word tests[136], and n-back tests for n = 0, 1, 2, and 3[52,137,138]), and a mood assessment (the Positive Affect and Negative Affect Schedule[133]). After the acclimatization period, participants completed an intuitive judgement test and three creativity tests (described in more detail in the Primary Outcome Measures: Creativity section and the Secondary Outcome Measure: Intuitive Judgement section in this chapter). Participants were not informed of the purpose of these tests. Following the creativity tests, participants completed the environmental questionnaire a fourth time. After completion of this questionnaire, participants left the study room and were debriefed.

A qualitative description each participant's clothing was recorded when participants entered the study room at the start of the study and when they left the study room at the end of the study. Clothing insulation values were estimated for each participant's clothing ensembles following the process outlined in Method 1 of Informative Appendix G in ANSI/ASHRAE Standard 55-2020.[3] Prior to analysis, all clothing insulation values were categorized as less than or equal to 0.57 clo (the clothing insulation value for trousers and a short-sleeve shirt, category as abbreviated as short-sleeve shirt below), equal to 0.61 clo (the clothing insulation value for trousers and a long-sleeve shirt, abbreviated as long-sleeve shirt below), and greater than 0.61 clo (abbreviated as jacket below).

After each participant completed all study activities, they were given a debriefing form with details about the study goals that were omitted from the initial consent form to ensure that participants remained blinded to study goals during their participation. After reading the debriefing form, participants were allowed to choose whether they gave permission for their study data to be used or whether they wanted their study data to be deleted.

All questionnaires and tests were administered through Qualtrics (Provo, UT, United States). Participants were compensated with $30 cash.

Exposure Measures: Temperature, Thermal Comfort, and Perceived Temperature

To account for any differences between thermostat temperature and actual room temperature, temperature in the waiting area and in the study room were measured by HOBO data loggers (model MX1102; Onset Computer Corporation, Bourne, MA, United States). In the waiting area, one HOBO data logger was placed on a chair seat or a table near the participant but out of their sight. In the study room, three HOBO data loggers were hidden from view with one attached to the underside of the participant's chair and two attached to opposite sides of the underside of the table where the participant was working. According to manufacturer specifications, these devices measure temperature with an accuracy of ±0.38 F, a range of 32-122 F, and a resolution of 0.04 F.[130] The HOBO data loggers also measured relative humidity (RH) and CO_2 concentrations with accuracies of ±2% (RH) and ±50 ppm (CO_2) over ranges of 1-70% RH and 0-5,000 ppm CO_2.[130] The manual calibration program for each HOBO data logger's CO_2 sensor was run each study day prior to participants' arrival. The display screens of the HOBO data loggers were cleared while participants were present. Outdoor temperature and RH were measured by an additional HOBO data logger made for outdoor use (model MX2300; Onset Computer Corporation, Bourne, MA, United States).

During their time in the study room, participants completed an environmental questionnaire four times. This questionnaire included questions about thermal comfort and perceived temperature, in addition to other questions designed to obscure the exposure of interest (e.g. questions about lighting, noise level, satisfaction with room appearance, how inspiring the room was, etc.). The question about thermal comfort asked participants to "Please rate how comfortable you are with the temperature in the room" on a continuous scale from -2 to 2 with labels at -2 (very uncomfortable), -1 (uncomfortable), 0 (neutral), 1 (comfortable), and 2 (very comfortable). The question about perceived temperature asked participants to "Please rate the temperature in the room" on a non-continuous but ordinal scale from -3 to 3 with labels at -3 (cold), -2 (cool), -1 (slightly cool), 0 (neutral), 1 (slightly warm), 2 (warm), and 3 (hot).

Primary Outcome Measures: Creativity

Three tests were used to measure the primary outcome of creativity: the compound remote associates test (cRAT), the alternative uses test (AUT), and the titles test. Titles test results were not included in this analysis due to concerns about whether the scoring method truly captured its intended domain of originality.

The cRAT is a common measure of convergent creative thinking, the ability to recognize associations between distant ideas to arrive at a correct solution to a problem.[139] In this study, participants were presented with 40 cRAT problems from an existing problem pool.[140] Each cRAT problem consisted of three words displayed on the computer screen. Participants had 15 seconds to solve each problem by typing a response word that made a compound word with each of the three words shown.[140,141] cRAT scores were calculated as the number of correct responses on the 40 problems. Throughput, the average time in milliseconds to enter correct responses, was also calculated, though this measure is not conventionally used in cRAT scoring. Higher cRAT scores represent better convergent creativity.

The AUT is a common measure of divergent creative thinking, the ability to develop original ideas when presented with problems that do not have correct or standard solutions.[142,143] In this study, the AUT was administered by showing participants the names of six common objects in sequence. For each object, participants were asked to type as many possible uses for the object as they could within two minutes. AUT scores were assigned for the domains of fluency (number of responses), originality (number of uncommon responses relative to responses from all participants), elaboration (amount of detail in responses), and flexibility (number of different categories represented in responses). This study's scoring procedure was based on several implementations of the AUT and related tests.[139,143,144] Before scoring, nonsense responses were removed. For each participant, scores for each domain were generated for each of the six objects separately and then averaged to generate one score per domain. Fluency scores were calculated as the number of responses. Elaboration scores were calculated as the mean number of words per response. To score originality, participants' responses were standardized (e.g. "doorstop" and "holding a door open" were both standardized as "doorstop"). Originality scores were calculated as the number of a participant's standardized responses that were given by fewer than 5% of participants. To score flexibility, standardized responses were grouped into function categories. Flexibility scores were calculated as the number of distinct function categories assigned to participants' answers. Higher scores for fluency, elaboration, originality, and flexibility represent better divergent creativity.

Secondary Outcome Measure: Intuitive Judgement

One test was used to measure the secondary outcome of intuitive judgement. This test evaluated the ability to judge the semantic coherence of word triads without consciously accessing information about them.[129,145] During the test, participants were presented with 24 sets of three words (word triads) in sequence. Twelve of the word triads were coherent (i.e. weakly related to a fourth word by meaning or because they made compound words). The remaining twelve word triads were incoherent. Participants were shown each word triad for 4 seconds and were then asked to indicate with a keystroke whether they thought the three words were coherent or not. When a participant indicated that a triad was coherent, they were asked to type a one-word solution to the triad (in 11 seconds or less) before continuing to the next triad. All word triads were drawn from the original test.[145] Scores for the intuitive judgement test were assigned following the procedure used by Bolte et al.[129] Briefly, a "hit rate" was calculated for each participant by dividing the number of unsolved coherent triads that were correctly classified as coherent by the total number of unsolved coherent triads. A “false alarm rate” was calculated for each participant by dividing the number of incoherent triads that were falsely classified as coherent by the total number of incoherent triads. Finally, the intuition index was calculated for each participant as the difference between their hit rate and their false alarm rate. Throughput, the average time in milliseconds to enter correct solutions to coherent triads that were judged coherent, was also calculated, though this measure is not conventionally used in scoring this test. The intuition index can range from -1 to 1. A higher intuition index represents better intuitive judgement.

Statistical Modeling

We used generalized linear models with binomial error distribution families to evaluate the predictors of thermal comfort by gender. Thermal comfort was dichotomized as greater than or equal to neutral (i.e. ≥ 0 on thermal comfort scale, abbreviated as thermally comfortable below) and less than neutral (i.e. <0 on thermal comfort scale, abbreviated as thermally uncomfortable below). Predictors in these models included the mean of in-room temperature measurements made by one HOBO data logger under the table while the participant was in the study room, the mean of in-room RH measurements made by the same HOBO data logger, the mean outdoor temperature over the hour before the participant entered the waiting area, and participant clothing when leaving the study room. Separate models were made for male and female participants. All participants in the analytic population were used in these models, with the exception of seven participants for whom there were errors recording measured indoor temperature, indoor RH, or outdoor temperature. Statistical significance for these model results was evaluated at α=0.05.

We also used generalized linear models with gaussian error distribution families and with bias-corrected and accelerated bootstrapped 95% confidence intervals (CIs) to evaluate the relationships between air temperature and (1) primary creativity outcomes (cRAT score and AUT fluency, originality, flexibility, and elaboration scores); (2) the secondary intuitive judgement outcome (intuition index); and (3) tertiary throughput outcomes (throughput on cRAT and intuitive judgement test). Because the temperatures chosen as thermostat setpoints were not always achieved while participants were in the room, air temperature in these models was represented by actual measured room temperature rather than by the thermostat setpoint. Unadjusted models were used to examine associations between each outcome and measured temperature, represented by the mean of in-room temperature measurements made by one of the HOBO data loggers under of the table while the participant was in the study room. Adjusted models were also used to examine associations between each outcome and measured temperature; these models included additional covariates representing the mean of in-room RH measurements made by one HOBO data logger under the table while the participant was in the study room, baseline creative personality measured in the waiting area by the IPIP scale, and categories of clothing worn when leaving the study room. Prior to modeling, IPIP baseline creative personality scores had been generated by reverse coding the five negatively keyed items in the scale and then summing the response values (from one to five) for all ten questions to arrive at a score ranging from ten to 50. Penalized splines on measured temperature indicated that the relationships between temperature and the outcomes of interest were approximately linear over the range of temperatures in this study, so final unadjusted and adjusted models of measured temperature used a linear term for this exposure. All models of measured temperature were stratified by gender. Model effect estimates were considered statistically significant when their bootstrapped 95% CIs did not cross zero.

Finally, we used permutation tests to evaluate whether people who reported thermal comfort less than neutral (i.e. thermally uncomfortable) just prior to outcome testing had, on average, different test scores than people who reported thermal comfort greater than or equal to neutral (i.e. thermally comfortable) for (1) primary creativity outcomes, (2) the secondary intuitive judgement outcome, and (3) tertiary throughput outcomes. These tests were stratified by gender. Statistical significance for permutation tests was evaluated at α=0.05 and suggestive evidence was evaluated at α=0.10.

Data from all participants in the analytic population were used in the thermal comfort permutation tests for the primary and secondary outcomes. The thermal comfort permutation tests for cRAT throughput used data from the analytic population after the removal of four participants who did not answer any cRAT questions correctly (and thus could not have a throughput score calculated) and of one additional participant for whom there was an error recording cRAT response time. The thermal comfort permutation tests for throughput on the intuitive judgement test used data from the analytic population after the removal of 13 participants who did not provide any correct solution words to this test (and thus could not have a throughput score calculated). Finally, the unadjusted models using measured temperature as the exposure used the same datasets as were used for the thermal comfort permutation tests, with the additional removal of three participants for whom there were errors recording measured temperature. The adjusted models using measured temperature as the exposure used the same datasets as were used for the unadjusted models with measure temperature as the exposure, with the additional removal of two participants for whom there were errors recording RH measurements.

All statistical modeling was performed using R version 4.0.2.

Results

Participant Characteristics

The target sample size for this study was 200 participants, but recruitment ended in early March 2020 after the COVID-19 pandemic forced the Harvard Decision Science Lab to shut down and then to close permanently. Before the lab shut down, a total of 88 people completed all study activities. Of those 88, four people withdrew consent during the debriefing process and their study data were deleted accordingly. An additional four people did not adequately complete the creativity and intuitive judgement tests, so their data were also removed from the analysis. Finally, the two participants who indicated that their gender was "other" or "prefer not to say" were removed from the analytic population to facilitate stratification by gender. The final analytic population consisted of 78 participants.

Characteristics of participants in the analytic population are shown in Table 4.2. This young adult (median age 22 years) analytic population was majority (65%) female. Most of the participants had either a full-time or part-time job, though 45% of participants were not employed, and the majority of participants (65%) were full-time students. Participant baseline creative personality measured by the IPIP scale and clothing insulation when leaving the study room are also shown in Table 4.2.

Table 4.2: Participant characteristics for all 78 participants in the analytic population.

	Median [Range] or n (%)
Age (years)	22 [18-36]
Baseline IPIP creative personality score	36 [25-47]
Gender	
Female	51 (65%)
Male	27 (35%)
Race	
White	38 (49%)
Asian	12 (15%)
Black or African American	10 (13%)
Hispanic, Latin, or Spanish origin of any race	2 (3%)
Two or more races	14 (18%)
Prefer not to say	2 (3%)
Highest level of school completed	
High school graduate	11 (14%)
Some college or 2-year degree	36 (46%)
4-year degree	18 (23%)
Advanced degree	13 (17%)
Current student	
Yes, full-time student	51 (65%)
Yes, part-time student	4 (5%)
No	23 (29%)
Currently employed	
Yes, full-time	13 (17%)
Yes, part-time	30 (38%)
No	35 (45%)
Overall physical health	
Slightly, moderately, or extremely good	71 (91%)
Neither good nor bad	2 (3%)
Slightly, moderately, or extremely bad	5 (6%)
Overall mental health	
Slightly, moderately, or extremely good	52 (67%)
Neither good nor bad	7 (9%)
Slightly, moderately, or extremely bad	19 (24%)
Clothing when leaving study room	
Short-sleeve shirt (≤ 0.57 clo)	37 (47%)
Long-sleeve shirt (0.61 clo)	23 (29%)
Jacket (> 0.61 clo)	18 (23%)

Indoor Environment

The measured temperatures in the study room often deviated from thermostat setpoints, particularly for higher setpoints (Table 4.3). When the thermostat was set to 82 F, the median of mean room temperatures measured under the table and away from the door during study participation was only 76.7 F. Similarly, when the thermostat was set to 76 F, the median of room temperatures in the same location was 73.8 F. Measurements from the three HOBO data loggers in the study room were similar to each other and indicated the presence of slight vertical and horizontal temperature gradients in the room. Balometer measurements indicate that airflow into the room ranged from 46 cubic feet per minute (cfm) to 73 cfm on study days. In-duct CO_2 measurements indicated that no outdoor air was introduced to the lab by the mechanical ventilation system during study participation.

Table 4.3: Temperature, RH, and CO_2 measurements outdoors and in the waiting area and study room and airflow measurements in the study room. Median [range] of conditions is shown.

	Conditions for All Participants Combined	**Conditions for Participants Assigned to Each of the Four Targeted Thermostat Temperature Setpoints**			
		68 F	**72 F**	**76 F**	**82 F**
Outdoor, mean of 1 hour before starting study					
Temperature (F), n=73	44.7 [25.3-58.4]	45.7 [39.8-57.5]	42.5 [33.1-48.9]	46.2 [39.5-58.4]	42.4 [25.3-55.6]
RH (%), n=73	50 [18-85]	71 [48-85]	36 [24-59]	51 [24-83]	33 [18-78]
Waiting area, mean of time participant in room					
Temperature (F), n=75	68.9 [66.2-77.3]	68.2 [66.2-74.9]	68.7 [66.6-70.5]	69.9 [67.6-77.3]	69.1 [66.5-74.1]
RH (%), n=71	26 [13-93]	33 [19-39]	25 [14-30]	29 [16-93]	27 [13-34]
CO_2 (ppm), n=75	577 [471-943]	560 [498-696]	582 [472-899]	589 [471-943]	580 [515-771]
Study room, mean of time participant in room					
Temperature (F)					
Under chair, n=75	71.8 [64.9-79]	65.5 [64.9-67.1]	71.3 [67.4-73.9]	72 [69.9-74.1]	74.3 [72.1-79]
Under table close to door, n=75	72.8 [64.9-77.7]	65.8 [64.9-70.3]	72 [70.2-74.1]	73.1 [70.9-74.8]	76.4 [74.3-77.7]
Under table far from door, n=75	73.5 [65.5-78.6]	66.5 [65.5-67.8]	72.5 [69.3-75.0]	73.8 [71.8-76.6]	76.7 [74.5-78.6]
RH (%)					
Under chair, n=69	25 [14-44]	32 [22-44]	23 [16-31]	30 [18-35]	22 [14-29]
Under table close to door, n=66	25 [12-46]	38 [22-46]	23 [16-29]	26 [17-33]	19 [12-30]
Under table far from door, n=73	26 [12-49]	38 [22-49]	25 [16-29]	28 [17-33]	22 [12-32]
CO_2 (ppm)					
Under chair, n=75	715 [505-942]	674 [587-803]	746 [505-942]	709 [619-866]	747 [630-890]
Under table close to door, n=75	713 [542-928]	641 [591-809]	763 [542-928]	714 [620-897]	734 [638-906]
Under table far from door, n=75	729 [539-934]	660 [570-772]	755 [539-932]	729 [636-893]	764 [636-934]
Study room, airflow measured once a day (cfm), n=32	56 [46-73]	72 [68-73]	52 [50-56]	51 [46-63]	70 [55-73]

Participant Thermal Comfort and Perceived Temperature

Thermal comfort (reported on a continuous scale from -2 to 2) was impacted by both room temperature and time in room for females but not for males (Figure 4.1A). When room temperatures were 65.5-70 F, females became less comfortable as time in the room elapsed. Males exposed to temperatures 65.5-70 F, on the other hand, commonly reported their thermal comfort as neutral or better at all four points of questioning. Perceived temperature (reported on an ordinal scale with seven options) was impacted by room temperature for both females and males, but only females' perceived temperature was impacted by time (Figure 4.1B). The ten females exposed to temperatures 65.5-70 F commonly felt slightly cool (30%) or cool (50%) upon entering the room; by the time they finished outcome testing (median 94, range 83-112 minutes after entering study room) nine of these same females reported feeling cold, and the remaining one female reported feeling cool. The six males exposed to temperatures 65.5-70 F also commonly reported feeling slightly cool (33%) or cool (33%) upon entering the room. However, males' perceived temperature, like their thermal comfort, did not change much over time.

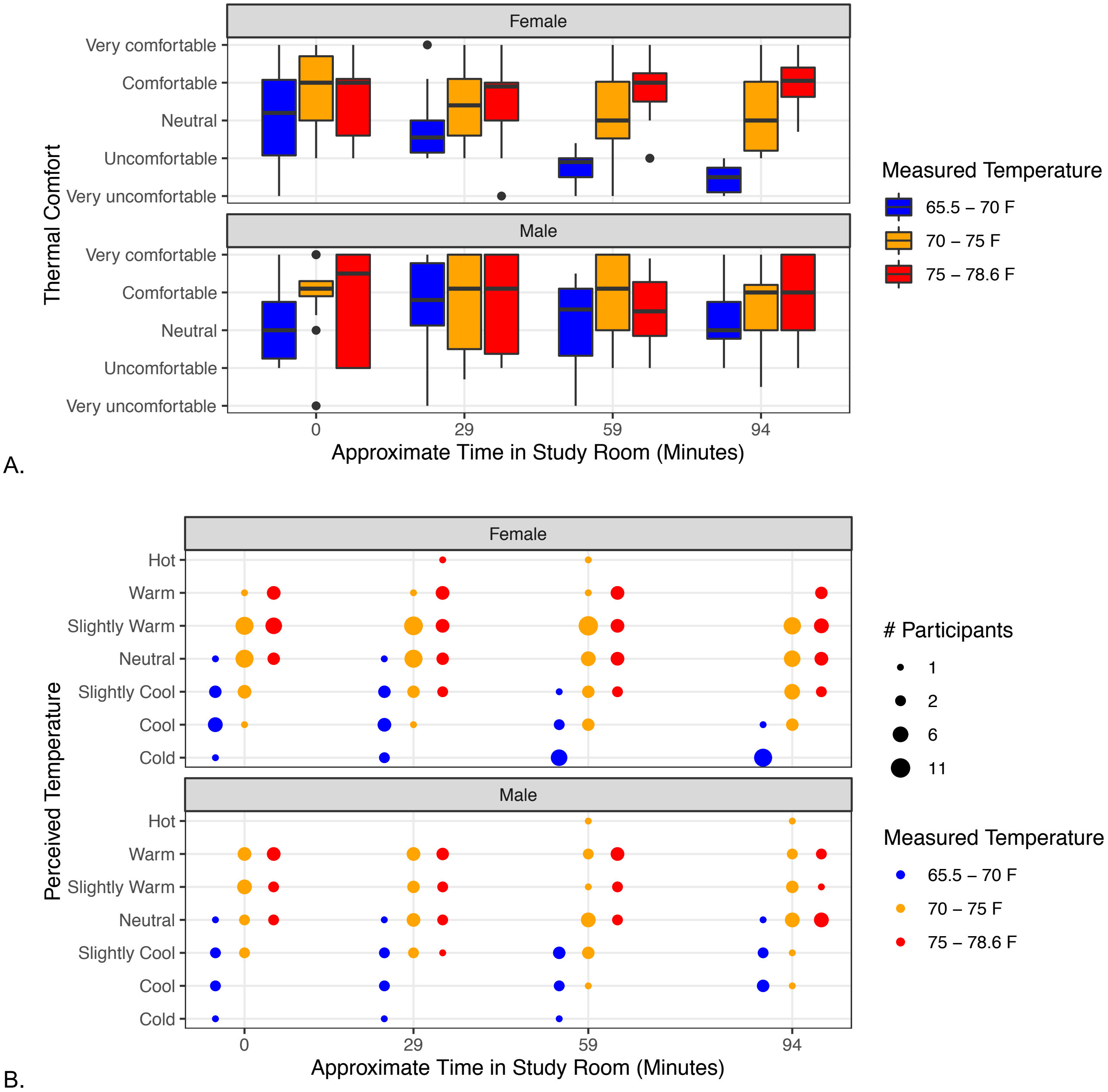

Figure 4.1: Trajectories of thermal comfort reported on a continuous scale from -2:Very uncomfortable to 2:Very comfortable (Figure 4.1A) and of perceived temperature reported on an ordinal scale from -3:Cold to 3:Hot (Figure 4.1B) over time, for males and females who experienced average study room temperatures of 65.5-70 F, 70-75 F, and 75-78.6 F. Time in study room shown on the x-axis is the median time between entering the study room and starting the environmental questionnaire containing the thermal comfort and perceived temperature questions.

Among females, the odds of reporting being thermally comfortable (i.e. thermal comfort rating ≥ 0) after a median of 59 minutes (range 51-81 minutes) in the study room increased significantly by 56% for a 1 F increase in room temperature, after controlling for room RH, outdoor temperature, and clothing (Table 4.4). Room temperature was not significantly associated with thermal comfort among males. Among males, the odds of reporting being thermally comfortable dropped by 31% as room RH increased by 1% RH, after controlling for room temperature, outdoor temperature, and clothing. Room RH was not significantly associated with thermal comfort among females. The positive effects of increasing room temperature on females' thermal comfort and the negative effects of increasing room RH on males' thermal comfort can also be seen in the psychrometric chart presented in Figure 4.2. Clothing was not significantly associated with thermal comfort among males or females after controlling for room temperature, outdoor temperature, and room RH (Table 4.4).

Table 4.4: Model results presented as odds ratios with 95% CIs for reporting thermal comfort in the third environmental questionnaire (median 59 minutes after entering study room) as greater than or equal to neutral compared to less than neutral. Bold text indicates p<0.05.

	Females (n=47) OR (95% CI)	**Males (n=24) OR (95% CI)**
Indoor temperature (F)	**1.56 (1.19, 2.22)*****	0.73 (0.45, 1.03)
Indoor RH (%)	1.00 (0.83, 1.18)	**0.69 (0.45, 0.89)****
Outdoor temperature (F)	1.04 (0.89, 1.22)	1.16 (0.92, 1.57)
Clothing (Reference = Short-sleeve shirt [≤ 0.57 clo])		
Long-sleeve shirt (0.61 clo)	1.17 (0.21, 7.17)	4.03 (0.21, 163)
Jacket (> 0.61 clo)	1.42 (0.21, 10.9)	4.68 (0.21, 235)

$^{*}p<0.10$
$^{**}p<0.05$
$^{***}p<0.01$

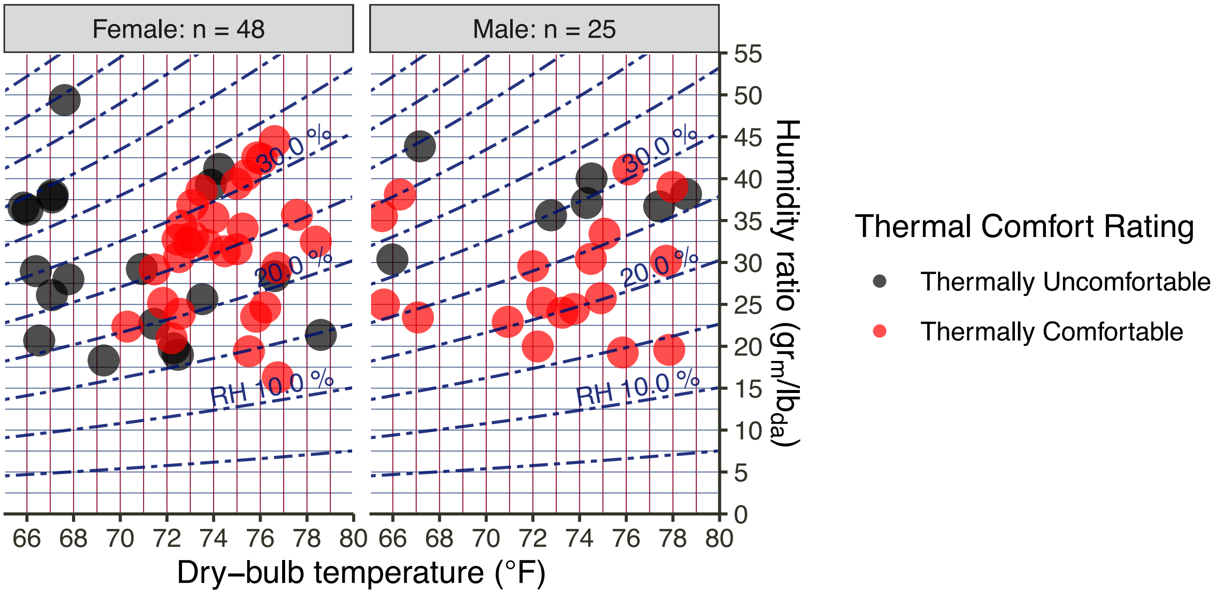

Figure 4.2: Self-reported thermal comfort after median 59 minutes (range 51-81 minutes) in the study room as a function of average study room temperature and humidity. This figure was produced using the R package ggpsychro.[146]

Relationships between Temperature and Creativity, Intuitive Judgement, and Throughput

There were no statistically significant associations between temperature and divergent or convergent creativity for males or females in adjusted or unadjusted models (Table 4.5). Nonetheless, in adjusted models for all five creativity outcomes for both males and females, the effect estimates for temperature were consistently positive, indicating that higher room temperatures across the range 65.5 F – 78.6 F may be associated with better performance on tests of convergent and divergent creativity. Based on the adjusted models for AUT fluency, an average score increase of 0.5 points in the AUT fluency domain (i.e. 0.5 more responses per object on AUT) is expected to result from a 12.4 F increase in room temperature for females and from a 4.4 F increase in room temperature for males, controlling for room RH, clothing, and baseline creative personality. Similarly, based on the adjusted models for cRAT scores, an average score increase of one point on the cRAT (i.e. solving one additional cRAT problem out of 40) is expected to result from an 11.3 F increase in room temperature for females and from a

3.8 F increase in room temperature for males, controlling for room RH, clothing, and baseline creative personality. In adjusted models, baseline creative personality was significantly associated with four creativity outcomes among females and two creativity outcomes among males, with higher baseline creativity predicting better performance on both the cRAT and AUT. For the secondary outcome of intuitive judgement, the effect estimates for temperature were negative for females and positive for males in both the unadjusted and adjusted models, though none of these effects were statistically significant. For the tertiary outcomes of throughput on the cRAT and the intuitive judgement test, results from the adjusted models showed that temperature was significantly positively associated with both throughput outcomes among females, indicating that performance was slower when temperatures were warmer. Among males, the effect estimates in adjusted models for both throughput outcomes were also positive, but not significantly so.

Table 4.5: Results of modeling creativity and intuitive judgement test scores and throughput as functions of measured room temperature. Bold text indicates where 95% CIs do not contain zero.

	Effect estimate (Bootstrapped 95% CI)			
	Divergent Creativity			
	AUT Fluency	**AUT Elaboration**	**AUT Flexibility**	**AUT Originality**
Unadjusted model (Females only)				
Temperature (F)	0.03 (-0.21, 0.24)	0.04 (-0.05, 0.15)	0.03 (-0.15, 0.15)	-0.02 (-0.14, 0.11)
Unadjusted model (Males only)				
Temperature (F)	0.02 (-0.14, 0.22)	0.08 (-0.06, 0.28)	0.03 (-0.10, 0.20)	-0.02 (-0.13, 0.09)
Adjusted model (Females only)				
Temperature (F)	0.04 (-0.28, 0.35)	0.04 (-0.08, 0.19)	0.04 (-0.16, 0.22)	0.01 (-0.15, 0.19)
RH (%)	0.01 (-0.10, 0.13)	0.00 (-0.07, 0.05)	0.01 (-0.07, 0.08)	0.02 (-0.05, 0.09)
Baseline creative personality	**0.14 (0.01, 0.27)**	0.03 (-0.05, 0.12)	**0.09 (0.01, 0.18)**	**0.10 (0.03, 0.19)**
Clothing (ref = Short-sleeve shirt [≤ 0.57 clo])				
Long-sleeve shirt (0.61 clo)	0.50 (-1.45, 2.48)	0.35 (-0.67, 1.70)	0.00 (-1.21, 1.33)	0.52 (-0.58, 1.78)
Jacket (> 0.61 clo)	-0.45 (-2.37, 1.85)	-0.06 (-1.16, 1.54)	-0.79 (-2.05, 0.54)	0.02 (-1.18, 1.29)
Adjusted model (Males only)				
Temperature (F)	0.11 (-0.08, 0.58)	0.01 (-0.17, 0.31)	0.12 (-0.05, 0.39)	0.05 (-0.09, 0.23)
RH (%)	0.05 (-0.08, 0.21)	-0.03 (-0.20, 0.07)	0.07 (-0.04, 0.17)	0.03 (-0.04, 0.15)
Baseline creative personality	0.14 (-0.01, 0.32)	0.03 (-0.11, 0.28)	**0.13 (0.02, 0.26)**	**0.09 (0.01, 0.19)**
Clothing (ref = Short-sleeve shirt [≤ 0.57 clo])				
Long-sleeve shirt (0.61 clo)	0.57 (-1.09, 2.89)	-0.54 (-2.46, 0.78)	0.38 (-0.99, 1.88)	0.53 (-0.87, 1.58)
Jacket (> 0.61 clo)	-1.40 (-3.53, 1.60)	-1.15 (-2.52, 0.59)	-1.62 (-3.23, 0.19)	-0.56 (-1.82, 0.61)

Table 4.5 (Continued).

	Effect estimate (Bootstrapped 95% CI)			
	Convergent Creativity	**Intuitive Judgement**	**Throughput (ms)**	
	cRAT	**Intuition Index**	**cRAT**	**Intuitive Judgement**
Unadjusted model (Females only)				
Temperature (F)	0.19 (-0.24, 0.62)	-0.006 (-0.025, 0.010)	105 (-24, 220)	**158 (44, 340)**
Unadjusted model (Males only)				
Temperature (F)	0.06 (-0.46, 0.61)	0.021 (-0.001, 0.037)	9 (-219, 177)	67 (-12, 130)
Adjusted model (Females only)				
Temperature (F)	0.09 (-0.63, 0.62)	-0.013 (-0.030, 0.003)	**144 (21, 260)**	**139 (20, 334)**
RH (%)	-0.12 (-0.37, 0.12)	-0.007 (-0.013, 0.002)	46 (-23, 102)	-15 (-98, 31)
Baseline creative personality	**0.27 (0.01, 0.53)**	-0.001 (-0.009, 0.007)	62 (-10, 118)	-77 (-199, 2)
Clothing (ref = Short-sleeve shirt [≤ 0.57 clo])				
Long-sleeve shirt (0.61 clo)	0.69 (-2.29, 4.34)	-0.029 (-0.124, 0.073)	-689 (-1540, 113)	120 (-746, 1498)
Jacket (> 0.61 clo)	-1.57 (-5.81, 2.93)	0.012 (-0.112, 0.185)	-273 (-1444, 967)	545 (-866, 3734)
Adjusted model (Males only)				
Temperature (F)	0.26 (-0.19, 0.77)	0.019 (-0.017, 0.043)	48 (-318, 285)	24 (-72, 144)
RH (%)	0.21 (-0.04, 0.48)	-0.006 (-0.022, 0.006)	12 (-142, 143)	-8 (-57, 46)
Baseline creative personality	0.16 (-0.16, 0.47)	-0.002 (-0.021, 0.014)	-51 (-322, 66)	-21 (-79, 37)
Clothing (ref = Short-sleeve shirt [≤ 0.57 clo])				
Long-sleeve shirt (0.61 clo)	**4.58 (0.88, 9.30)**	-0.001 (-0.282, 0.216)	904 (-1034, 3353)	-536 (-1272, 366)
Jacket (> 0.61 clo)	**-7.79 (-10.56, -3.17)**	0.144 (-0.038, 0.347)	1030 (-1370, 2718)	368 (-979, 1376)

Relationships between Thermal Comfort and Creativity, Intuitive Judgement, and Throughput

Permutation tests suggest that average scores on all four AUT outcomes were significantly or suggestively different between thermally uncomfortable females and thermally comfortable females, with thermally comfortable females scoring higher (Figure 4.3A). The difference in mean AUT fluency scores between thermally comfortable and thermally uncomfortable females was 1.50 points, indicating that the thermally comfortable females provided, on average, 1.50 more responses per object on the AUT than did the thermally uncomfortable females. Similarly, the difference in mean AUT originality scores between thermally comfortable and thermally uncomfortable females was 0.78 points, indicating that the thermally comfortable females provided, on average, 0.78 additional unique responses per object on the AUT than did the thermally uncomfortable females.

Additional comparisons of thermally comfortable and thermally uncomfortable people indicated that there were no significant or suggestive differences in performance on the cRAT among females or males or on the AUT among males (Figure 4.3). Both females and males who felt thermally comfortable had lower intuition indices than their counterparts who were thermally uncomfortable, but these differences were not significant (Figure 4.3). There were no significant or suggestive differences in throughput on the cRAT or intuitive judgement test among females or males comparing those who were thermally comfortable to those who were thermally uncomfortable (Figure 4.3).

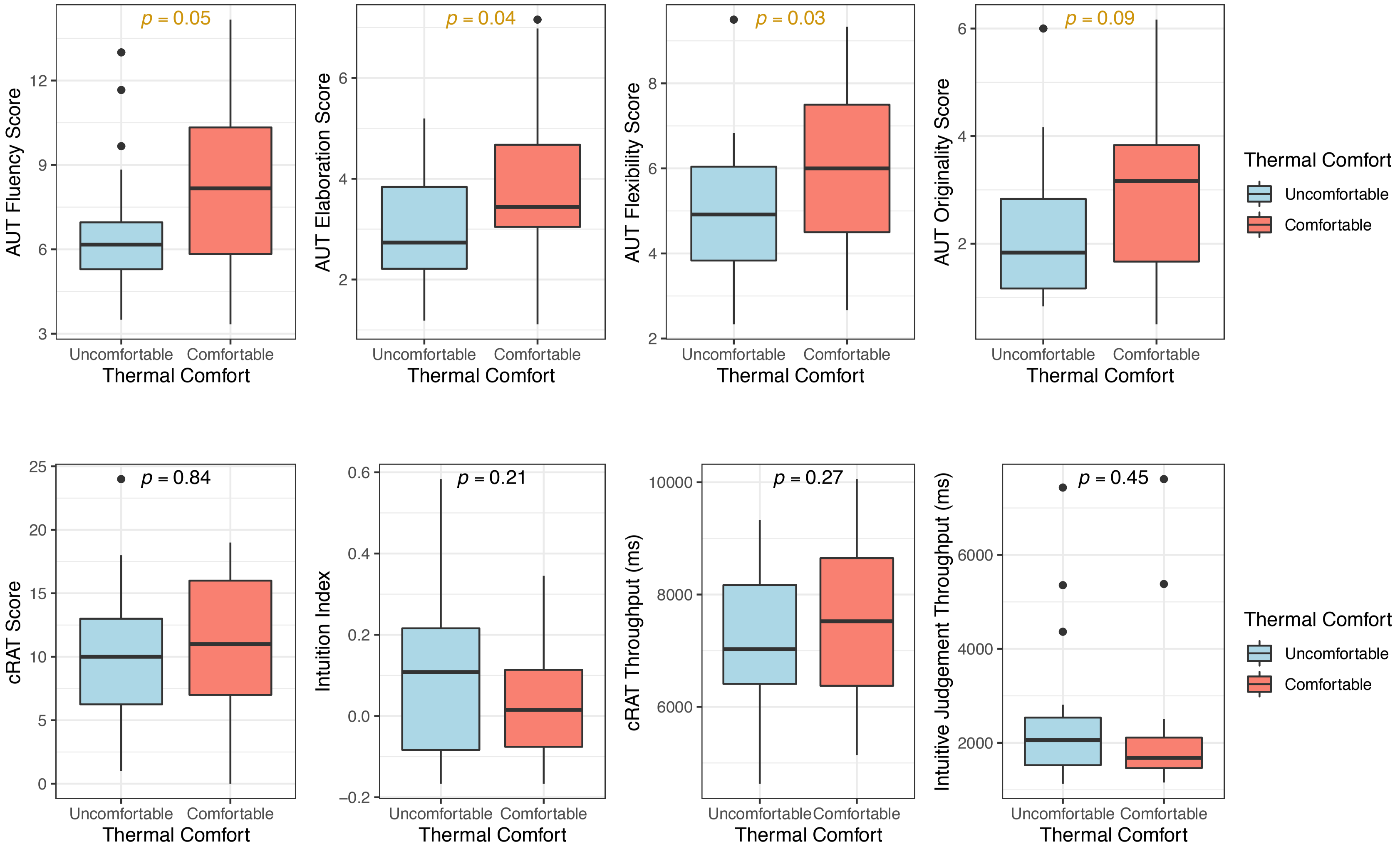

Figure 4.3A: Creativity and intuitive judgement test scores and throughput as a function of thermal comfort among females. The plots include p-values calculated using permutation tests to compare scores among females with thermal comfort less than neutral to females with thermal comfort greater than or equal to neutral. Gold text indicates p<0.10.

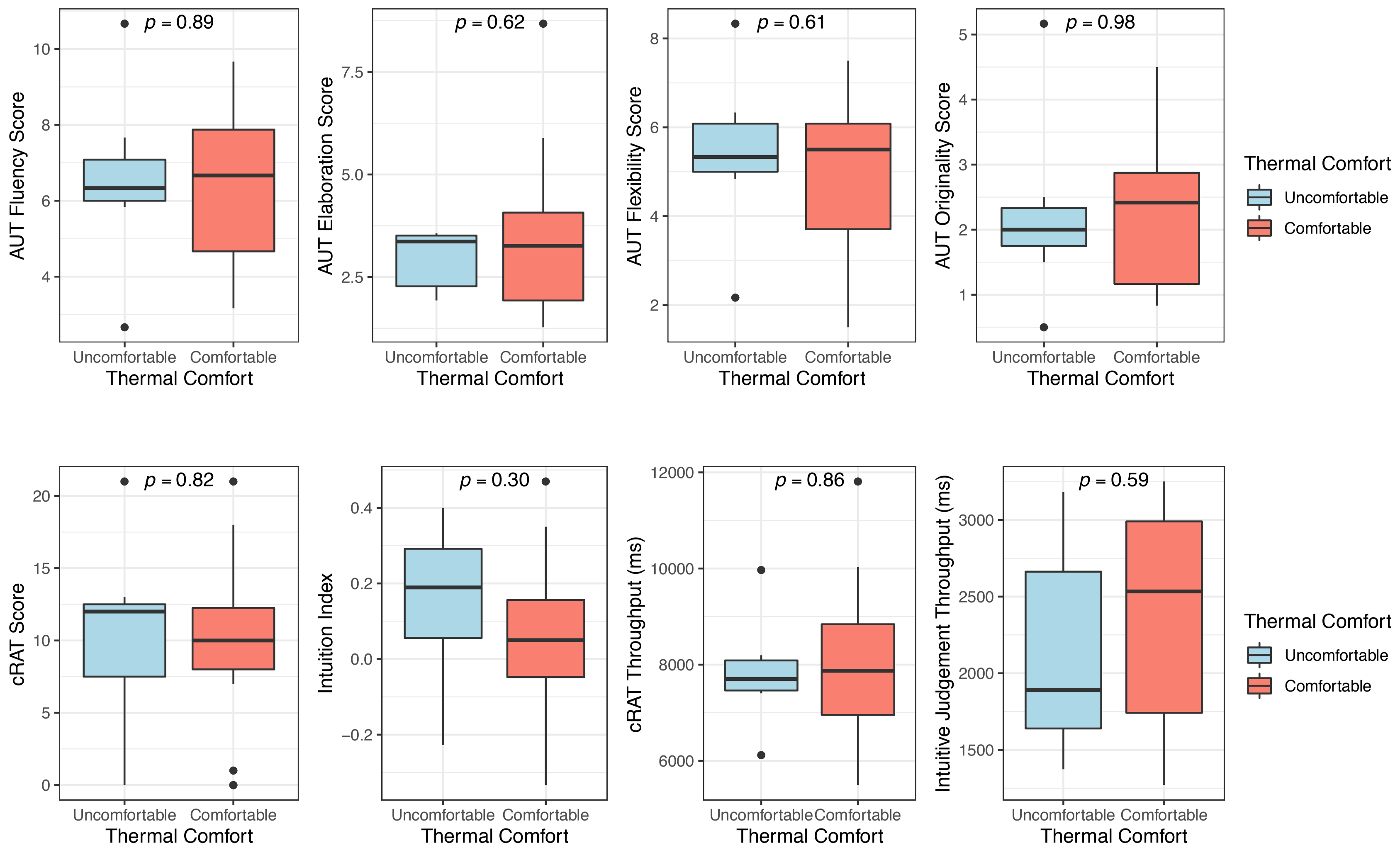

Figure 4.3B: Creativity and intuitive judgement test scores and throughput as a function of thermal comfort among males. The plots include p-values calculated using permutation tests to compare scores among males with thermal comfort less than neutral to males with thermal comfort greater than or equal to neutral.

Discussion

Our results suggest that warmer temperatures across the range of 65.5-78.6 F may promote divergent and convergent creativity and that thermal comfort is a significant predictor of divergent creativity. There was statistically significant or suggestive evidence that divergent creativity measured by all four AUT domains was higher among females who were thermally comfortable compared to females who were thermally uncomfortable. We did not observe an effect of thermal comfort on divergent creativity among males, but this may be due to this study's limited range of thermal exposure conditions which males generally found to be comfortable; only seven out of 27 males reported being thermally uncomfortable when asked just prior to outcome testing. While males' relative comfort in slightly cool temperatures has been documented previously,[116,121] this study is the first to link temperature and thermal comfort with divergent and convergent creativity.

Temperature and Creativity

Our finding that thermal conditions impact divergent creativity measured by the AUT adds to the body of prior work demonstrating that other environmental factors can impact creativity. For example, disorder,[126] complexity of visual detail,[125] ventilation rate,[72] and a general measure of the quality of the physical work environment[124] have been associated with creative performance measured by the AUT, collage making, and a creativity questionnaire. Speed or throughput on creativity tests is not usually evaluated, but having the ability to choose one's workstation has been associated with slower speed on a creativity test similar to the AUT.[147] Only one prior study has looked at the effect of temperature on creativity; this study investigated how temperature (71.6 F, 78.8 F, and 86.0 F) and noise (35 dBA and 55 dBA) impacted performance on the AUT after 25 minutes of exposure and found that normalized creativity scores were higher though not significantly so at 78.8 F compared to 71.6 F for participants in the 35 dBA condition.[128] This prior finding agrees with our results of non-significant increases in creativity measured by all four AUT domains as temperature increased across the range of 65.5 F to 78.6 F in adjusted models for males and females. Furthermore, we extended the prior result by finding that creativity appeared to increase as temperature increased at temperatures as low as 65.5 F, that the association between temperature and creativity appeared to be approximately linear between 65.5 F and 78.6 F, and that this relationship is present for convergent creativity scores on the cRAT in addition to divergent creativity scores on the AUT.

Our results suggest that the optimal temperature for creativity may be different than the optimal temperature for other cognitive tasks. While individual studies have found that temperatures as high as 78.4 F optimized performance on traditional cognitive tests,[51] metanalyses suggest that cognitive function and productivity are optimized around 71.6 F.[1,28] That said, several reviews also indicate that there may be different optimal conditions for different task types and for different test metrics (e.g. accuracy vs. reaction time).[2,29] Our results build on this idea in two ways. First, our finding that creativity improves with temperatures across the range of 65.5-78.6 F, which agrees with and builds on prior work using the AUT,[128] suggests that the optimal temperature for divergent and convergent creativity may be higher than 71.6 F, the temperature that is optimal for traditional measures of work performance.[1] Second, our results also suggest that the optimal temperature for creativity may not be the same as the optimal temperature for throughput. While creativity scores in our study tended to increase with temperature across the exposure range, throughput on the cRAT and the intuitive judgement test among males and females tended to be faster when temperatures were cool, though only significantly so among females. Although the cRAT and intuitive judgement test are not traditional cognitive tests, this result is aligned with a metanalysis that reported that cold exposure resulted in improved reaction times on cognitive tests, though not on psychomotor or perception tests.[29]

Thermal Comfort and Creativity

Although the relationships between temperature and all five creativity scores were consistently positive in adjusted models, they were not statistically significant; however, thermal comfort was significantly or suggestively associated with scores on all four AUT domains among females. Prior researchers have suggested that the effect of temperature on traditional tests of cognitive function is not primarily mediated by distraction due to discomfort at cold or hot temperatures, but is instead the result of physiological changes that occur at cool or warm temperatures.[54] However, our finding that thermal comfort was significantly associated with divergent creativity suggests that distraction due to thermal discomfort, rather than any temperature-induced physiological changes, may be primarily responsible for the impact of thermal conditions on divergent creativity scores. The existence of different mechanisms for the impact of thermal conditions on different types of cognitive tests may be related to whether they rely on associative thought (which involves finding connections between ideas that are not closely related) or analytic thought (which is more focused evaluation of on a single idea).[148] Both types of thought are required to score well on creativity tests like the cRAT and the AUT, but traditional productivity tests like addition tests or the Stroop color-word test primarily rely on analytic thought. Our results may indicate that divergent creative tests that rely on associative thought are impacted more by discomfort-induced distraction than traditional productivity measures are.

Gender Differences in Thermal Comfort and Creativity

Our finding of gender differences in how cold temperatures (65.5-70 F) were perceived and preferred aligns with the findings of two prior reviews of thermal comfort research that determined that females tend to feel more uncomfortable than males when temperatures are slightly cool.[116,121] We found that when the study room was 65.5-70 F, females and males both tended to rate the temperature as cool or slightly cool upon entering, but females perceived the temperature to be colder and became more uncomfortable over time while males' thermal perceptions and comfort did not change over time (Figure 4.1). While clothing is sometimes suggested as a reason for thermal comfort discrepancies between males and females,[121] gender differences in clothing do not explain the difference in thermal comfort that developed over the course of this study. A chi-squared test of independence (χ^2=0.33, p=0.85) suggests that clothing did not vary across the two genders in our study and the effect of clothing on thermal comfort after approximately 59 minutes in the study room was not significant among females or males, after controlling for indoor temperature, indoor RH, and outdoor temperature (Table 4.4). In our study, it appears more likely that physiological differences, such as differences in metabolic rate[149] and blood circulation,[150] rather than gendered clothing differences were responsible for females' increased thermal discomfort in cool conditions.

We also found gender differences in associations between thermal comfort and divergent creativity outcomes (Figure 4.3), as the significant and suggestive impacts of thermal comfort on AUT scores was only present among females. It is possible that the lack of a significant association between thermal comfort and divergent creativity among males stems from their relative comfort in all experimental conditions. Of the 27 males in the experiment, only seven reported being thermally uncomfortable just before the outcome testing began. It is possible that an association between thermal comfort and divergent creativity might be observed among males if this study were repeated with lower temperatures that more males found uncomfortable.

Temperature, Thermal Comfort, and Intuitive Judgement

Our results suggest that males and females who felt thermally comfortable performed worse on a test of intuitive judgement than those who felt thermally uncomfortable though these results were not statistically significant. To our knowledge, there is no prior work linking intuitive judgement to thermal conditions, but prior work does indicate that intuitive judgements can be influenced by psychological cues and conditions like priming and mood, with more positive moods associated with better intuitive judgement.[129,151] In our data, intuition index scores were not significantly associated with mood scores on the Positive Affect and Negative Affect Schedule or on a question asking about self-reported mood (from negative:0 to positive:100), perhaps indicating that external factors including thermal comfort may interfere with the influence of mood on intuition. More work should be done to understand how environmental factors influence intuitive judgement.

Implications for Office Buildings

Our results indicate that buildings' target environmental conditions should take gender-specific thermal comfort into account to maximize occupant performance. We found that females were more sensitive to slightly cold conditions than males were and that this discomfort in slightly cool conditions impacted divergent creativity. If buildings targeted thermal conditions that females found comfortable, they could support females' divergent creativity without detrimentally impacting males' creativity. This recommendation of using females' more narrow range of thermal comfort to define indoor environmental conditions that both males and females would find comfortable has been proposed previously.[116] To date, the standard that guides thermal design and operations in buildings in the United States, ANSI/ASHRAE Standard 55-2020,[3] does not account for any differences in thermal preferences between males and females except by implicitly suggesting that females' office wear may be less insulating then males'. Our results suggest that by updating thermal comfort standards to account for differences between optimal conditions for males and females, creativity among males and females can be optimized. Alternatively, buildings could use personal comfort systems to deliver personalized thermally comfortable conditions for individual building occupants.[121]

Strengths & Limitations

The main limitation of our study was that the analytic population (78 participants) was only 39% of its intended size (200 participants). This limitation resulted from the lab facility's shut down and then permanent closure due to the COVID-19 pandemic. With the smaller population, we had less power to detect statistically significant effects. However, even with the smaller population, our study found directionally consistent effects of temperature on creativity and several statistically significant effects of thermal comfort on divergent creativity among females. A second limitation of our study was that the actual range of study room temperatures (65.5-78.6 F) was lower and smaller than the intended range of temperatures (68-82 F). Nonetheless, our study did cover an exposure range of 13.1 F and prior work has found measurable differences on various non-creative cognitive tests, such as arithmetic tests and tests of alertness or attention, over temperatures similar to those used in this study.[51,55,56,152] Moreover, in contrast to prior work that used short pre-test acclimatization periods (5-25 minutes) and found no significant effects of thermal variables on tests of performance,[128,153,154] our study used a pre-test acclimatization period of at least 54 minutes (median 63 minutes, maximum 86 minutes). Pre-test acclimatization periods of 40-70 minutes can result in significant differences on non-creative cognitive tests[51,52,55,56,155] and the American Society of Heating, Refrigerating and Air-Conditioning Engineers indicates that one hour of acclimatization time is sufficient to wash out effects of prior thermal conditions,[3] so our study should have been able to measure any temperature-induced differences in performance that exist across the range of exposure temperatures. Finally, this study assessed the primary outcome of interest, creativity, using five different domains calculated from two different tests, making it the first study to evaluate the effects of thermal conditions on convergent creativity and on all four AUT domains of divergent creativity. The results of our study are generalizable to young adults working in settings where thermal conditions are similar to those commonly found in office buildings in the United States. Our results may not generalize to older adults, as aging affects cognitive function[138,156] and our study only included participants aged 18-36 years, or to office workers in other regions who may be acclimated to different thermal conditions.

Conclusion

This study is the first to explore how thermal conditions impact divergent and convergent creativity and intuitive judgement. Our results suggest that divergent and convergent creativity may be maximized at higher temperatures across the range of 65.5-78.6 F, which means creativity may be optimized by higher temperatures than those that optimize other aspects of work performance. Importantly, our results also show that divergent creativity is significantly worse among individuals who are not thermally comfortable. This association was only observed among females, who tended to be more uncomfortable than males in slightly cool temperatures (65.5-70 F). In offices where divergent creative work is carried out, building operators can optimize performance by ensuring that thermal comfort for males and females is maintained.

CHAPTER 5: CONCLUSION

The goals of this dissertation were to address gaps in knowledge about the impacts of office building design and operations on indoor environmental quality (IEQ) and to add nuance to our understanding of how IEQ impacts both previously-studied and unstudied aspects of office worker health and work performance. The findings of this dissertation emphasize the important role that workplace IEQ plays in supporting worker health and performance and indicate that solutions for improving workplace IEQ exist.

Summary of Findings

Study 1 characterized indoor fine particulate matter ($PM_{2.5}$) in a cohort of office buildings from the Global CogFx Study. This one-year longitudinal study of office workers in buildings on multiple continents was the first of its kind and provided an opportunity to perform several unique IEQ analyses. We found that indoor $PM_{2.5}$ was generally lower than outdoor $PM_{2.5}$, but did exceed health-based guidelines during work hours in China and India. The results of our statistical modeling point to solutions for reducing indoor $PM_{2.5}$ exposures. First, the magnitude of the association between indoor and outdoor $PM_{2.5}$ during work hours was smaller than during non-work hours, suggesting that operating ventilation systems protect indoor air quality by, for example, maintaining pressurization in buildings and preventing infiltration. Second, higher efficiency filters were associated with substantially reduced indoor $PM_{2.5}$ concentrations, indicating that high-efficiency filters can protect office workers from exposures that may be harmful to their health while they are at work.

Study 2 characterized offices' indoor relative humidity (RH) levels and explored associations between indoor RH and occupant-reported symptoms using a cohort of office buildings from the Global CogFx Study. We found that it was more common for buildings to have low RH (<40% RH) compared to high RH (>60% RH). Indoor RH tended to be lowest among the buildings that were in less tropical regions, during winter months, when outdoor RH or temperature was low, and late in the workday. Low indoor RH was associated with increased reports of three symptoms among females (dry or itchy skin and two mucous membrane symptoms) and two symptoms among males (dry or itchy skin and unusual tiredness, fatigue or drowsiness).

Unlike Studies 1 and 2, which took place in situ in operating and occupied office buildings, Study 3 made use of a laboratory environment to test the impact of temperature and thermal comfort on intuitive judgement and two types of creativity. We found that males and females consistently performed better on the compound remote associates test, a test of convergent creativity, and on all four domains of the alternative uses test (AUT), a test of divergent creativity, as temperatures increased across the exposure range of 65.5-78.6 F, though these consistent, positive effects were not statistically significant. Females were more likely than males to report being thermally uncomfortable when temperatures were slightly cool (65.5-70 F). Females who reported feeling thermally uncomfortable scored significantly worse on three AUT domains (with suggestive evidence for the fourth AUT domain) than females who reported feeling thermally comfortable. These results highlight the importance of thermal comfort and warmer temperatures for office workers engaged in creative work.

Practical Implications of Findings

This dissertation demonstrates that IEQ in operating and occupied offices is not always conducive to building occupants' health and work performance. In Study 1, we saw that indoor

$PM_{2.5}$ sometimes exceeded the World Health Organization's (WHO's) 24-hour exposure guideline of 25 μg/m^3 during work hours, particularly in China and India. In Study 2, we saw that indoor RH can be very low, resulting in increases in occupant-reported symptoms, particularly in the United Kingdom. In Study 3, was saw that it was common for slightly cool air temperatures to be perceived as uncomfortable, particularly by females, which may result in compromised divergent creativity. However, this dissertation also points to solutions for these problems.

In the future, IEQ standards and guidelines can help create healthier and more productive indoor spaces. The WHO or other standards organizations may consider issuing indoor $PM_{2.5}$ exposure guidelines similar to their outdoor exposure guidelines. Though likely unenforceable, indoor exposure guidelines would help people who have access to indoor $PM_{2.5}$ data to understand when their indoor air quality is unacceptable. In Study 3, we saw that cooler temperatures tended to make females more uncomfortable than males. This result agrees with prior work on gender and thermal comfort[116,121] and was not explained by clothing. Consequently, guidelines for indoor thermal environments, such as ANSI/ASHRAE Standard 55,[3] should be updated to account for gender differences in sensitivity to deviations from neutral temperatures.

There are also measures that can be taken in existing buildings and new construction to support the health and performance of building occupants. In existing buildings, it may be possible to improve IEQ by installing higher efficiency filters to reduce indoor $PM_{2.5}$ or by controlling thermal conditions more tightly to ensure females and males both are thermally comfortable. Optimal thermal comfort could be achieved by setting building targets to a smaller range than that recommended by ANSI/ASHRAE Standard 55,[3] so deviations from neutral temperatures would be smaller and less frequent, or by setting up personal comfort systems to deliver individualized thermally comfortable conditions for each building occupant. The used of zoned ventilation or personal comfort systems is expected to be beneficial both for employee comfort and productivity and for building energy costs, as providing comfortable conditions for smaller individual workspaces means energy won't be wasted heating or cooling unused portions of the office.[121,157] Reductions in building energy use have implications for business operating costs, but also for society at large; building heating, ventilation, and air conditioning account for approximately 20% of energy use in developed countries,[157] so reducing this energy use could have a substantial beneficial impact on climate change. In new construction, IEQ can be supported by installing ventilation equipment that can handle high efficiency filters and that is designed to deliver sufficient outdoor air and to adjust both latent and sensible heat loads by humidification or dehumidification (e.g. energy recovery device, dedicated outdoor air system, variable air volume units with adiabatic humidification of outdoor air).

At a higher level, our work points to the ways in which the future of worker health may be facilitated by new technology. In our work, low-cost IEQ sensors were used for in situ IEQ monitoring in offices in Studies 1 and 2. The interest in these sensors for indoor and outdoor use has grown over the past decade, and has particularly accelerated in 2020 and 2021 due to an interest in using carbon dioxide measurements as a proxy for outdoor air exchange to evaluate the risk of airborne transmission of SARS-CoV-2 in indoor spaces. In this way, the COVID-19 pandemic has opened the eyes of a larger segment of the general population to the value of IEQ sensors for making visible the invisible or intangible IEQ parameters that impact human health and performance. In the future, we expect that these sensors will be used by businesses in offices or even in offsite workspaces (e.g. home offices, coworking spaces) to ensure worker productivity and health are protected or even optimized. Furthermore, some of these sensors are cheap enough and portable enough that they can also be used by individuals to confirm whether spaces they enter, including businesses or their own homes, have IEQ that protects their own health and performance. As the use of IEQ sensors in workplaces, homes, and public spaces increases, it would be beneficial for the WHO or other organizations to publish new guidelines for IEQ parameters so sensor users understand what their measurements mean and what they can do to improve poor IEQ. In the future, it is possible these sensors could be used to ensure that buildings meet new legally-required IEQ standards; however, such uses would first require improvements in the accuracy and longevity of the technology.

In addition to a wider adoption of IEQ sensors, our work also points to another way businesses may optimize their return on investment in their employees. As more and more rote tasks of office work are able to be automated, the focus of knowledge work will turn towards more creative thinking. Our results suggest that the temperatures that optimize creativity may be different from those that optimize traditional productivity metrics. As this result may generalize to other IEQ parameters, businesses should proactively consider how their existing office environments and work practices may require alterations in order to promote creativity.

Recommendations for Future Research

The findings of this dissertation point to several areas of future research.

First, the results of Studies 1 and 2 should be tested in other types of buildings with different ventilation, infiltration, and/or outdoor climate characteristics, including lower quality (e.g. Class C) office buildings, as well as in homes where the effects of indoor $PM_{2.5}$ and RH may be particularly important for people who work in their homes. Future work on indoor $PM_{2.5}$

should additionally consider how indoor $PM_{2.5}$ exposures are affected by portable air cleaners, open windows, ventilation system configuration, and total outdoor and recirculated airflows. For example, future research should consider the impact of ventilation schedules (e.g. start time of morning warm-up cycles after nights, weekends, or holidays) on building occupants' workday exposures and health. As a second example, future research should also consider how natural ventilation impacts IEQ, how supplemental filtration systems to remove $PM_{2.5}$ and allergens could improve air quality in naturally ventilated buildings, and how the energy required for supplemental filtration in naturally ventilated buildings compares to the energy saved by using natural rather than mechanical ventilation.

Additionally, the results of Study 3 should be expanded by evaluating intuitive judgement and creativity in more people exposed to a larger range of temperatures. A larger sample size would help determine the effect of temperature on intuitive judgement, which was inconclusive in this study. A larger range of temperature exposures would help determine the optimal temperature for convergent and divergent creativity, as it is possible this optimum exceeds the highest temperature in this study which was 78.6 F. Additional work may also look at other measures of creativity, such as actual performance of creative office work (e.g. design or development work), although this research would first require the creation of an objective, scalable scoring methodology. Furthermore, since creativity has long been under-studied in IEQ research, additional work should be undertaken to determine how variables like ventilation rate and the presence of indoor contaminants affect convergent and divergent creativity. Finally, the effect of IEQ on creativity in diverse populations, including primary and secondary school students and older adults in the workplace, should be studied.

Importantly, future research should also address how IEQ can be wholistically optimized in buildings without increasing their energy requirements. For example, future research should investigate how personal comfort systems, which improve individuals' thermal comfort, affect the distribution of indoor air contaminants (e.g. $PM_{2.5}$) and whether paring personal comfort systems with portable air cleaners with high-efficiency particulate air (HEPA) filters could further meaningfully improve IEQ. Additionally, future work should consider how IEQ can be optimized in homes and workplaces across all relevant parameters, how low-cost IEQ sensors can best be used to optimize IEQ in real time, and how incentives for businesses to make healthier products (e.g. range hoods that more effectively capture particles produced by all stove burners) or updates to building codes might lead to improved IEQ in homes and workplaces.

Concluding Remarks

In conclusion, this dissertation filled knowledge gaps and advanced our understanding of three ways in which building design and operations play an important role in supporting offices' IEQ, which in turn plays a key role in supporting occupants' health, comfort, and creativity at work. Making IEQ adjustments in existing buildings and investing in IEQ during construction of new buildings will benefit individual workers' health and performance which is expected to translate into improved satisfaction and productivity across companies. With the recent proliferation of low-cost IEQ sensors, the ongoing popularization of healthy building certifications, and unprecedented attention on indoor air quality due to the COVID-19 pandemic, the degree to which IEQ research impacts building design and operations is likely to increase in the near future.

APPENDIX A (FOR CHAPTER 2)

Table A1. *CO_2 sensor specifications for environmental sensor packages used in buildings from the Global CogFx Study included in this analysis.*

Package Name	**CO_2 Sensor Name**	**Type of CO_2 Sensor**	**Range (ppm)**	**Resolution (ppm)**	**Accuracy**	**Third Party Evaluation**
Harvard Healthy Buildings	SenseAir S8[a]	NDIR[b]	400-50,000[b]	NR	±200 ppm and ±10%[b]	NR
Tsinghua IBEM	NR	NDIR[c]	0-5,000[c]	1[c]	±75 ppm[c]	Examined by China National Institute of Metrology[c]
Awair Omni	Amphenol Telaire T6703-5 K[d]	NDIR[e]	0-5,000[e]	1[e]	±3% and ±50 ppm[e]	Interior RESET Air Accredited Grade B monitor[e,f]
ChemiSense CS-001	NR	NDIR[g]	400-5,000[g]	1[g]	400 - 2,000 ppm: ±50 ppm and ±3% 2,000 - 5,000 ppm: ±50 ppm and ±5%[g]	Interior RESET Air Accredited Grade B monitor[f]
Tongdy MSD-16	Amphenol Telaire T67X3[h]	NDIR[i]	0-5,000[i]	1[i]	±40 ppm and ±3%[i]	Interior RESET Air Accredited Grade B monitor[f]

NDIR: Non-dispersive infrared

NR: Not reported

[a] Harvard Healthy Buildings sensors were constructed by the authors and their colleagues using SenseAir S8 miniature infrared CO_2 sensors.

[b] SenseAir S8 Specification Sheet: "Data sheet and manual: SenseAir S8 Alarm 5% Miniature infrared CO_2 sensor module" by CO2meter.com.

[c] Y. Geng, B. Lin, J. Yu, H. Zhou, W. Ji, H. Chen, Z. Zhang, Y. Zhu, Indoor Environmental Quality of Green Office Buildings in China: Large-Scale and Long-Term Measurement, Build. Environ. 150 (2019) 266–280. https://doi.org/10.1016/j.buildenv.2019.01.014.

[d] I. Demanega, I. Mujan, B.C. Singer, A.S. Anđelković, F. Babich, D. Licina, Performance assessment of low-cost environmental monitors and single sensors under variable indoor air quality and thermal conditions, Build. Environ. 187 (2021) 107415. https://doi.org/10.1016/j.buildenv.2020.107415.

[e] RESET™ Specification Sheet for AWAIR Omni Indoor Air Quality Monitor.

[f] RESET™ Accredited Monitors webpage (https://www.reset.build/monitors).

[g] RESET™ Air Accredited Monitor Testing Report for ChemiSense CS-001.

[h] Tongdy MSD-16 sensors are presumed to use Amphenol Telaire T6703 or T6713 based on observation of deconstructed sensors.

[i] MSD Sensors Specification Sheet: "MSD IAQ Detector – User Manual V.1707" by Tongdy Sensing Technology Corporation.

Table A2. *Detailed summary of hourly measurements of indoor $PM_{2.5}$ by country and month, shown separately for standard work hours (weekdays 9:00 – 17:00 local time, abbreviated as “W”) and non-work hours (weekends and weekdays before 7:00 or after 19:00 local time, abbreviated as “NW”).*

			Indoor $PM_{2.5}$ ($\mu g/m^3$)										
Country	**Month**	**Hours**	**Min**	**1st %ile**	**5th %ile**	**25th %ile**	**Median**	**Mean**	**75th %ile**	**95th %ile**	**99th %ile**	**Max**	**# $PM_{2.5}$ Data**
China	Mar - May	W	1.0	1.0	1.0	10.5	18.3	19.4	24.9	40.2	72.6	426.4	11,194
		NW	1.0	2.5	4.8	11.1	17.2	17.9	23.3	34.0	48.0	120.1	29,234
	Jun - Aug	W	0.0	0.0	1.0	5.3	11.8	14.4	19.4	33.7	71.5	334.0	10,747
		NW	0.0	0.0	2.0	5.1	9.9	11.3	16.0	25.4	35.2	110.2	29,230
	Sep - Nov	W	0.0	1.0	1.6	10.5	20.0	20.7	27.3	44.0	72.6	176.6	10,314
		NW	0.0	2.2	4.8	10.5	18.3	18.8	24.5	37.8	53.3	189.7	25,573
	Dec - Feb	W	1.0	1.0	2.5	12.2	21.7	23.0	28.5	52.5	83.8	203.4	10,714
		NW	0.8	2.2	5.5	13.0	20.8	21.7	27.5	44.5	60.0	169.7	26,923
India	Mar - May	W	0.0	0.0	0.0	11.2	17.5	19.0	25.7	40.8	49.7	57.0	485
		NW	0.0	0.0	0.0	16.2	23.2	24.4	34.7	42.8	51.1	82.8	1,055
	Jun - Aug	W	0.0	0.0	0.0	4.0	6.0	6.6	8.5	15.0	21.0	34.8	3,012
		NW	0.0	0.0	0.0	5.7	8.8	9.7	12.5	21.7	34.2	155.8	8,033
	Sep - Nov	W	0.0	0.0	0.0	5.6	9.2	12.2	15.7	36.0	47.0	71.3	2,502
		NW	0.0	0.0	0.0	7.0	12.0	16.2	21.0	44.8	55.8	157.0	6,199
	Dec - Feb	W	0.0	0.0	7.5	19.2	28.6	39.4	42.2	136.3	220.5	249.6	534
		NW	0.0	0.0	10.3	29.3	45.2	46.8	58.3	95.9	137.2	197.6	956
UK	Mar - May	W	0.0	0.0	0.0	0.4	1.0	2.1	2.2	6.5	11.7	500.0	13,282
		NW	0.0	0.0	0.0	1.0	1.5	2.3	2.8	7.5	13.3	216.7	36,759
	Jun - Aug	W	0.0	0.0	0.0	0.0	0.8	1.1	1.5	3.5	5.8	77.2	9,404
		NW	0.0	0.0	0.0	0.0	1.0	1.6	2.0	4.5	8.8	431.0	24,574
	Sep - Nov	W	0.0	0.0	0.0	0.0	0.0	0.8	0.4	3.8	12.3	27.6	1,320
		NW	0.0	0.0	0.0	0.0	0.2	1.3	1.3	5.8	17.1	31.5	3,543
	Dec - Feb	W	0.0	0.0	0.0	0.7	1.8	3.0	3.2	8.3	14.2	311.7	4,674
		NW	0.0	0.0	0.0	1.6	3.4	4.6	6.0	14.0	20.0	85.0	11,311
USA	Mar - May	W	0.0	0.0	0.0	0.5	1.2	2.9	4.6	10.0	13.9	166.5	21,788
		NW	0.0	0.0	0.0	0.7	1.8	3.3	5.3	10.5	14.4	81.2	54,226
	Jun - Aug	W	0.0	0.0	0.0	0.8	2.3	3.6	6.2	10.3	12.9	62.7	22,906
		NW	0.0	0.0	0.0	1.0	2.9	3.8	5.8	10.8	13.0	396.0	61,230
	Sep - Nov	W	0.0	0.0	0.0	0.2	1.7	3.4	5.8	11.3	14.4	104.2	15,213
		NW	0.0	0.0	0.0	0.3	2.7	3.9	6.2	12.1	14.5	116.6	38,298
	Dec - Feb	W	0.0	0.0	0.0	0.1	1.4	3.5	6.0	11.8	18.7	120.2	17,810
		NW	0.0	0.0	0.0	0.2	1.7	3.6	6.3	12.1	14.4	90.0	45,223

Table A3. *Detailed summary of hourly measurements of outdoor $PM_{2.5}$ by country and month, shown separately for standard work hours (weekdays 9:00 – 17:00 local time, abbreviated as "W") and non-work hours (weekends and weekdays before 7:00 or after 19:00 local time, abbreviated as "NW").*

			Outdoor $PM_{2.5}$ ($\mu g/m^3$)										
Country	**Month**	**Hours**	**Min**	**1st %ile**	**5th %ile**	**25th %ile**	**Median**	**Mean**	**75th %ile**	**95th %ile**	**99th %ile**	**Max**	**# $PM_{2.5}$ Data**
China	Mar - May	W	0.0	2.0	8.0	16.0	27.0	34.4	46.0	85.0	112.0	154.0	11,194
		NW	0.0	4.0	8.0	17.0	28.0	34.3	44.0	84.0	123.0	192.0	29,234
	Jun - Aug	W	0.0	2.0	5.0	12.0	20.0	23.8	32.0	56.0	75.1	106.0	10,747
		NW	0.0	1.4	3.0	10.0	19.0	22.2	31.0	51.0	69.7	144.0	29,230
	Sep - Nov	W	0.0	6.0	10.0	19.0	28.0	34.6	44.0	81.0	137.0	173.0	10,314
		NW	0.0	5.0	9.0	18.6	28.0	34.5	41.0	88.0	123.0	183.0	25,573
	Dec - Feb	W	0.0	5.0	10.0	22.0	35.0	44.1	58.0	105.0	152.0	228.0	10,714
		NW	0.0	6.0	10.0	21.0	35.0	43.7	59.0	103.0	147.0	186.0	26,923
India	Mar - May	W	0.0	0.0	11.3	26.2	32.2	39.1	39.0	122.7	161.9	182.2	485
		NW	0.0	4.4	14.0	28.9	37.0	47.0	50.3	126.2	179.7	308.8	1,055
	Jun - Aug	W	0.0	0.0	2.0	8.0	13.0	16.4	21.0	34.4	64.9	845.8	3,012
		NW	0.0	0.0	1.7	7.5	12.2	16.4	19.5	40.5	73.8	844.1	8,033
	Sep - Nov	W	0.0	0.0	4.0	11.2	16.9	21.7	27.4	51.5	79.5	320.0	2,502
		NW	0.0	0.0	4.0	11.0	17.1	23.1	28.0	58.8	109.0	470.3	6,199
	Dec - Feb	W	24.3	30.0	34.1	56.0	77.3	92.8	117.0	192.0	273.5	494.9	534
		NW	10.8	23.6	32.0	53.5	75.0	90.7	118.0	198.0	259.0	583.8	956
UK	Mar - May	W	2.0	3.0	4.0	7.0	10.0	13.3	15.0	38.0	49.0	83.0	13,282
		NW	3.0	3.0	5.0	7.0	10.0	13.9	16.0	37.0	49.0	61.0	36,759
	Jun - Aug	W	1.0	3.0	4.0	5.0	7.0	7.5	9.0	14.0	24.9	30.0	9,404
		NW	1.0	3.0	4.0	5.0	7.0	7.4	9.0	14.0	21.0	27.0	24,574
	Sep - Nov	W	2.0	3.2	5.0	6.0	7.0	9.8	10.0	23.0	37.0	105.0	1,320
		NW	2.0	3.0	4.0	6.0	7.0	9.6	11.0	22.0	37.6	90.0	3,543
	Dec - Feb	W	3.0	4.0	6.0	9.0	14.0	20.5	31.8	47.0	61.0	74.0	4,674
		NW	0.0	5.0	6.0	10.0	20.0	21.9	30.0	47.0	53.0	63.0	11,311
USA	Mar - May	W	0.0	0.0	1.0	4.5	7.0	7.6	10.0	16.0	21.0	156.9	21,788
		NW	0.0	0.0	1.6	4.6	7.5	8.4	11.0	19.0	27.0	560.6	54,226
	Jun - Aug	W	0.0	0.0	1.3	5.0	8.0	8.8	11.8	18.0	27.2	146.4	22,906
		NW	0.0	0.0	2.0	5.2	8.3	9.6	13.0	20.8	27.0	111.0	61,230
	Sep - Nov	W	0.0	0.0	1.0	4.1	7.0	8.1	10.8	18.0	26.5	86.0	15,213
		NW	0.0	0.0	1.3	4.2	7.0	8.1	10.5	18.0	27.0	62.0	38,298
	Dec - Feb	W	0.0	0.0	1.2	4.9	7.0	8.6	11.0	20.0	31.1	86.2	17,810
		NW	0.0	0.0	1.4	4.8	7.2	8.7	11.0	20.2	31.3	82.7	45,223

Table A4. *Detailed summary of hourly measurements of indoor CO_2 by country and month, shown separately for standard work hours (weekdays 9:00 – 17:00 local time, abbreviated as "W") and non-work hours (weekends and weekdays before 7:00 or after 19:00 local time, abbreviated as "NW").*

			Indoor CO_2 (ppm)										
Country	**Month**	**Hours**	**Min**	**1st %ile**	**5th %ile**	**25th %ile**	**Median**	**Mean**	**75th %ile**	**95th %ile**	**99th %ile**	**Max**	**# CO_2 Data**
China	Mar - May	W	400	400	412	460	511	529	575	696	883	1,849	10,457
		NW	400	400	400	406	423	445	457	583	640	880	25,120
	Jun - Aug	W	400	406	435	509	567	596	659	840	976	1,453	10,341
		NW	400	400	400	403	421	445	458	571	718	1,213	25,826
	Sep - Nov	W	400	400	413	475	532	556	608	776	982	1,854	9,802
		NW	400	400	400	410	432	460	478	614	756	1,104	22,443
	Dec - Feb	W	400	400	415	491	552	603	654	978	1,312	1,971	10,445
		NW	400	400	400	409	431	460	475	621	755	1,801	23,560
India	Mar - May	W	400	408	429	524	630	793	920	1,729	2,150	4,714	453
		NW	400	402	406	423	473	564	566	1,138	1,655	3,439	1,010
	Jun - Aug	W	407	425	476	638	753	816	933	1,254	2,145	4,366	3,012
		NW	400	400	404	423	460	524	543	873	1,311	4,162	7,937
	Sep - Nov	W	400	401	415	516	711	775	966	1,325	1,900	2,892	2,484
		NW	400	401	409	430	470	549	562	996	1,335	2,444	6,076
	Dec - Feb	W	441	473	513	667	1,058	1,091	1,467	1,806	2,124	2,250	534
		NW	401	405	425	488	560	630	683	1,125	1,453	1,874	944
UK	Mar - May	W	400	404	448	666	750	780	889	1,107	1,245	1,951	13,282
		NW	400	400	401	416	434	457	466	605	751	1,448	36,756
	Jun - Aug	W	400	458	565	700	796	817	933	1,114	1,233	2,373	9,184
		NW	400	400	404	416	433	467	477	622	1,024	2,190	23,819
	Sep - Nov	W	455	480	548	672	790	807	910	1,148	1,350	1,638	1,257
		NW	400	401	404	415	447	473	501	638	755	1,080	3,230
	Dec - Feb	W	421	442	538	662	740	776	850	1,151	1,313	1,530	4,643
		NW	400	400	400	419	456	483	508	681	835	1,024	11,092
USA	Mar - May	W	400	421	454	514	578	627	681	998	1,316	2,439	21,754
		NW	400	400	402	417	444	492	514	733	1,023	2,627	50,220
	Jun - Aug	W	400	418	457	533	604	653	709	1,025	1,499	1,857	22,897
		NW	400	400	403	420	458	501	530	727	1,184	1,681	58,379
	Sep - Nov	W	400	405	435	519	589	643	702	1,087	1,344	1,594	15,040
		NW	400	400	402	417	443	492	508	776	1,083	1,475	35,430
	Dec - Feb	W	400	402	439	541	617	671	732	1,175	1,362	1,688	17,593
		NW	400	400	402	418	441	497	504	814	1,124	1,531	42,414

APPENDIX B (FOR CHAPTER 3)

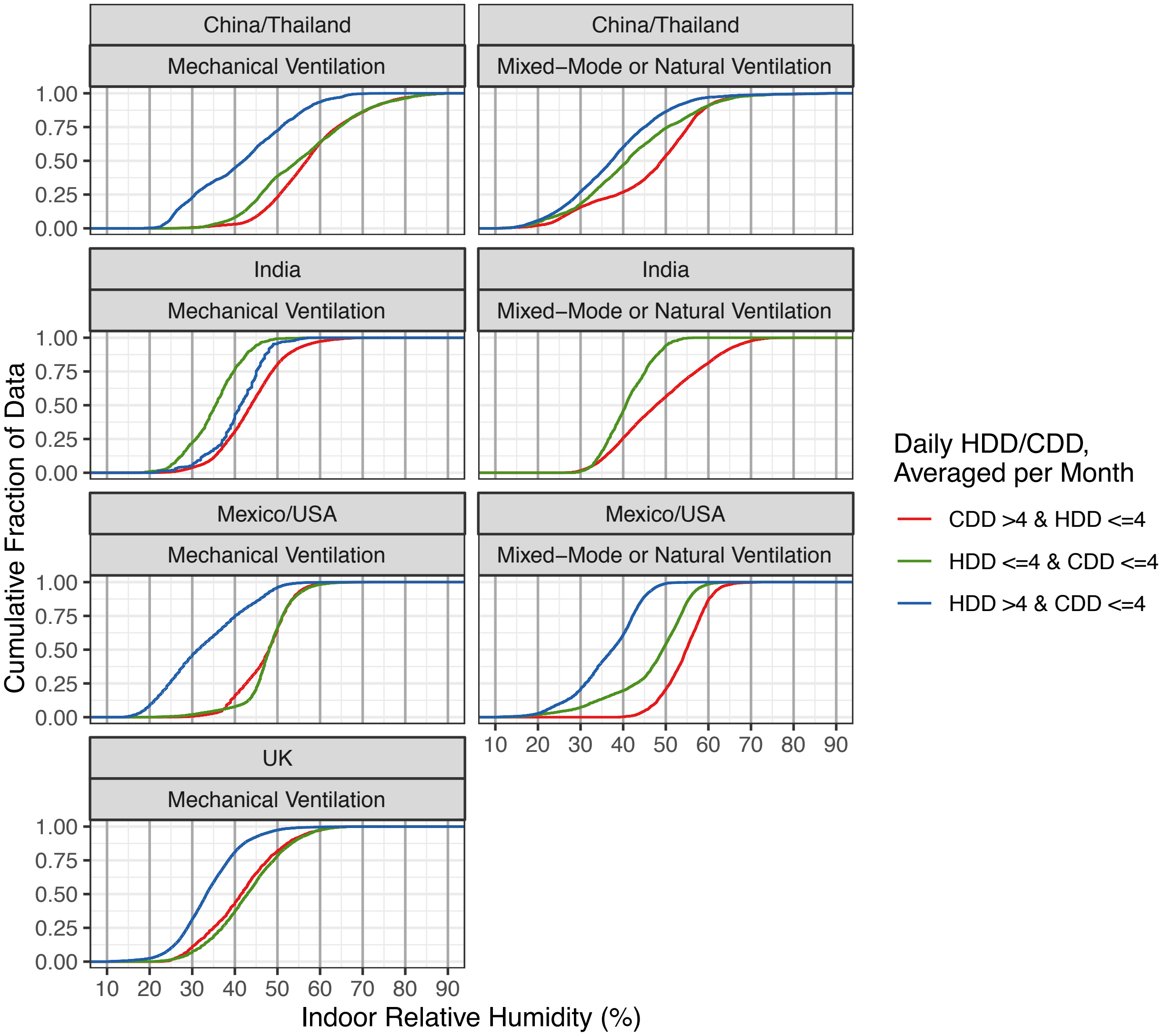

Figure B1. *Cumulative distribution functions of hourly device average indoor RH measurements on weekdays between 9:00 and 17:00 by ventilation type, heating- or cooling-dominated conditions, and region in the buildings in the Global CogFx Study. In this analysis, heating-dominated months were defined as months when the mean daily HDDs exceeded four and the mean daily CDDs did not exceed four. Similarly, cooling-dominated months were defined as months when the mean daily CDDs exceeded four and the mean daily HDDs did not exceed four. Months when neither heating nor cooling conditions dominated were defined as months when mean daily HDDs and mean daily CDDs both did not exceed four.*

BIBLIOGRAPHY

1. Seppänen, O., Fisk, W. J. & Lei, Q. *Effect of Temperature on Task Performance in Office Environment*. (2006).

2. Yeganeh, A. J., Reichard, G., McCoy, A. P., Bulbul, T. & Jazizadeh, F. Correlation of ambient air temperature and cognitive performance: A systematic review and meta-analysis. *Build Environ* **143**, 701–716 (2018).

3. ASHRAE. *ANSI/ASHRAE Standard 55-2020: Thermal Environmental Conditions for Human Occupancy*. (2021).

4. Pope, C. A. *et al.* Lung Cancer, Cardiopulmonary Mortality, and Long-term Exposure to Fine Particulate Air Pollution. *JAMA* **287**, 1132–1141 (2002).

5. Lipsett, M. J. *et al.* Long-Term Exposure to Air Pollution and Cardiorespiratory Disease in the California Teachers Study Cohort. *Am J Respir Crit Care Med* **184**, 828–835 (2011).

6. Dockery, D. W. *et al.* An Association between Air Pollution and Mortality in Six U.S. Cities. *New Engl J Med* **329**, 1753–1759 (1993).

7. Burnett, R. *et al.* Global Estimates of Mortality Associated with Long-Term Exposure to Outdoor Fine Particulate Matter. *PNAS* **115**, 9592–9597 (2018).

8. Feenstra, R. C., Inklaar, R. & Timmer, M. P. The Next Generation of the Penn World Table. *Am Econ Rev* **105**, 3150–3182 (2015).

9. Rosner, D. & Markowitz, G. A Short History of Occupational Safety and Health in the United States. *Am J Public Health* **110**, 622–628 (2020).

10. Rosner, D. & Markowitz, G. "Educate the Individual... to a Sane Appreciation of the Risk": A History of Industry's Responsibility to Warn of Job Dangers Before the Occupational Safety and Health Administration. *Am J Public Health* **106**, 28–35 (2016).

11. Weinstock, D. & Failey, T. The Labor Movement's Role in Gaining Federal Safety and Health Standards to Protect America's Workers. *New Solut* **24**, 409–434 (2014).

12. Occupational Safety and Health Administration. *Workers' Rights*. https://www.osha.gov/sites/default/files/publications/osha3021.pdf (2017).

13. Occupational Safety and Health Administration. *Indoor Air Quality in Commercial and Institutional Buildings*. (2011).

14. Redlich, C. A., Sparer, J. & Cullen, M. R. Sick-building syndrome. *Lancet* **349**, 1013–1016 (1997).

15. Spengler, J. D. & Sexton, K. Indoor Air Pollution: A Public Health Perspective. *Science* **221**, 9–17 (1983).

16. Spengler, J. D. Indoor air pollution. *N Engl Reg Allergy Proc* **6**, 126–134 (1985).

17. Womble, S. E. *et al.* Developing Baseline Information on Buildings and Indoor Air Quality (BASE '94): Part I -Study Design, Building Selection, and Building Descriptions. in *Healthy Buildings '95* (1995).

18. Lee, K., Levy, J. I., Yanagisawa, Y., Spengler, J. D. & Billick, I. H. The Boston residential nitrogen dioxide characterization study: classification and prediction of indoor NO2 exposure. *J Air Waste Manag Assoc* **48**, 736–742 (1998).

19. Levy, J. I., Lee, K., Spengler, J. D. & Yanagisawa, Y. Impact of residential nitrogen dioxide exposure on personal exposure: an international study. *J Air Waste Manag Assoc* **48**, 553–560 (1998).

20. Dodson, R. E. *et al.* Measured and Modeled Personal Exposures to and Risks from Volatile Organic Compounds. *Environ Sci Technol* **41**, 8498–8505 (2007).

21. Dodson, R. E., Levy, J. I., Spengler, J. D., Shine, J. P. & Bennett, D. H. Influence of basements, garages, and common hallways on indoor residential volatile organic compound concentrations. *Atmos Environ* **42**, 1569–1581 (2008).

22. Allen, J. G. *et al.* 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. *Environ Health Perspect* **124**, 805–812 (2016).

23. MacNaughton, P. *et al.* The impact of working in a green certified building on cognitive function and health. *Build Environ* **114**, 178–186 (2017).

24. ASHRAE. *ANSI/ASHRAE Standard 62.1-2019: Ventilation for Acceptable Indoor Air Quality*. (2019).

25. Janssen, J. E. The History of Ventilation and Temperature Control. *ASHRAE J* 47–52 (1999).

26. ASHRAE. *ANSI/ASHRAE Standard 52.2-2017: Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size*. (2017).

27. Mendell, M. J. & Mirer, A. G. Indoor thermal factors and symptoms in office workers: findings from the US EPA BASE study. *Indoor Air* **19**, 291–302 (2009).

28. Pilcher, J. J., Nadler, E. & Busch, C. Effects of Hot and Cold Temperature Exposure on Performance: A Meta-Analytic Review. *Ergonomics* **45**, 682–698 (2002).

29. Hancock, P. A., Ross, J. M. & Szalma, J. L. A Meta-Analysis of Performance Response Under Thermal Stressors. *Hum Factors* **49**, 851–877 (2007).

30. Gilson, L. L. & Shalley, C. E. A Little Creativity Goes a Long Way: An Examination of Teams' Engagement in Creative Processes. *J Manage* **30**, 453–470 (2004).

31. Zhang, X. & Bartol, K. M. The influence of creative process engagement on employee creative performance and overall job performance: A curvilinear assessment. *J Appl Psychol* **95**, 862–873 (2010).

32. Kahneman, D. *Thinking, Fast and Slow*. (Farrar, Straus and Giroux, 2013).

33. Klepeis, N. E. *et al.* The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. *J Expo Sci Env Epid* **11**, 231–252 (2001).

34. Matz, C. J., Stieb, D. M. & Brion, O. Urban-rural differences in daily time-activity patterns, occupational activity and housing characteristics. *Environ Health* **14**, (2015).

35. Spalt, E. W. *et al.* Time-Location Patterns of a Diverse Population of Older Adults: The Multi-Ethnic Study of Atherosclerosis and Air Pollution (MESA Air). *J Expo Sci Env Epid* **26**, 349–355 (2016).

36. Zhao, Y. *et al.* Microenvironmental time-activity patterns in Chongqing, China. *Front Environ Sci Engin China* **3**, 200–209 (2009).

37. Casanova, L. M., Jeon, S., Rutala, W. A., Weber, D. J. & Sobsey, M. D. Effects of Air Temperature and Relative Humidity on Coronavirus Survival on Surfaces. *Appl Environ Microbiol* **76**, 2712–2717 (2010).

38. Chan, K. H. *et al.* The Effects of Temperature and Relative Humidity on the Viability of the SARS Coronavirus. *Adv Virol* **2011**, 1–7 (2011).

39. Lin, K. & Marr, L. C. Humidity-Dependent Decay of Viruses, but Not Bacteria, in Aerosols and Droplets Follows Disinfection Kinetics. *Environ Sci Technol* **54**, 1024–1032 (2020).

40. Lowen, A. C., Mubareka, S., Steel, J. & Palese, P. Influenza Virus Transmission Is Dependent on Relative Humidity and Temperature. *PLoS Pathog* **3**, (2007).

41. Marr, L. C., Tang, J. W., Van Mullekom, J. & Lakdawala, S. S. Mechanistic insights into the effect of humidity on airborne influenza virus survival, transmission and incidence. *J R Soc Interface* **16**, (2019).

42. Morris, D. H. *et al.* Mechanistic theory predicts the effects of temperature and humidity on inactivation of SARS-CoV-2 and other enveloped viruses. *bioRxiv* (2020) doi:https://doi.org/10.1101/2020.10.16.341883.

43. Myatt, T. A. *et al.* Modeling the airborne survival of influenza virus in a residential setting: the impacts of home humidification. *Environ Health* **9**, 55 (2010).

44. Arens, E. A. & Baughman, A. V. Indoor Humidity and Human Health: Part II--Buildings and Their Systems. *ASHRAE Tran* **102**, 212–221 (1996).

45. United States Environmental Protection Agency. *Mold Remediation in Schools and Commercial Buildings*. https://www.epa.gov/sites/production/files/2014-08/documents/moldremediation.pdf (2008).

46. Derby, M. M. *et al.* Update of the scientific evidence for specifying lower limit relative humidity levels for comfort, health, and indoor environmental quality in occupied spaces (RP-1630). *Sci Technol Built Environ* **23**, 30–45 (2017).

47. Lukcso, D., Guidotti, T. L., Franklin, D. E. & Burt, A. Indoor environmental and air quality characteristics, building-related health symptoms, and worker productivity in a federal government building complex. *Arch Environ Occup Health* **71**, 85–101 (2016).

48. Nakano, J., Tanabe, S. & Kimura, K. Differences in perception of indoor environment between Japanese and non-Japanese workers. *Energy Build* **34**, 615–621 (2002).

49. Reinikainen, L. M. & Jaakkola, J. J. K. Significance of humidity and temperature on skin and upper airway symptoms. *Indoor Air* **13**, 344–352 (2003).

50. Lind, M., Holøs, S., Thunshelle, K., Yang, A. & Mysen, M. How Does Low Relative Humidity Affect Perceived Air Quality, Thermal Comfort and Symptoms in Modern Office Buildings in Cold Climates? in *Cold Climate HVAC 2018* 899–909 (Springer, Cham, 2019). doi:10.1007/978-3-030-00662-4_76.

51. Cui, W., Cao, G., Park, J. H., Ouyang, Q. & Zhu, Y. Influence of Indoor Air Temperature on Human Thermal Comfort, Motivation and Performance. *Build Environ* **68**, 114–122 (2013).

52. Maula, H. *et al.* The Effect of Slightly Warm Temperature on Work Performance and Comfort in Open-Plan Offices – A Laboratory Study. *Indoor Air* **26**, 286–297 (2016).

53. Cedeño Laurent, J. G. *et al.* Reduced Cognitive Function during a Heat Wave among Residents of Non-Air-Conditioned Buildings: An Observational Study of Young Adults in the Summer of 2016. *PLOS Med* **15**, e1002605 (2018).

54. Lan, L., Wargocki, P., Wyon, D. P. & Lian, Z. Effects of Thermal Discomfort in an Office on Perceived Air Quality, SBS Symptoms, Physiological Responses, and Human Performance. *Indoor Air* **21**, 376–390 (2011).

55. Lan, L., Lian, Z., Pan, L. & Ye, Q. Neurobehavioral Approach for Evaluation of Office Workers' Productivity: The Effects of Room Temperature. *Build Environ* **44**, 1578–1588 (2009).

56. Schiavon, S., Yang, B., Donner, Y., Chang, V. W.-C. & Nazaroff, W. W. Thermal Comfort, Perceived Air Quality, and Cognitive Performance when Personally Controlled Air Movement is Used by Tropically Acclimatized Persons. *Indoor Air* **27**, 690–702 (2017).

57. Ellis, H. D. The Effects of Cold on the Performance of Serial Choice Reaction Time and Various Discrete Tasks. *Hum Factors* **24**, 589–598 (1982).

58. Makinen, T. *et al.* Effect of repeated exposures to cold on cognitive performance in humans. *Physiol Behav* **87**, 166–176 (2006).

59. Palinkas, L. A. *et al.* Influence of seasonally adjusted exposure to cold and darkness on cognitive performance in circumpolar residents. *Scand J Psychol* **46**, 239–246 (2005).

60. Kioumourtzoglou, M.-A. *et al.* Long-term PM2.5 Exposure and Neurological Hospital Admissions in the Northeastern United States. *Environ Health Perspect* **124**, 23–29 (2016).

61. Dominici, F. *et al.* Fine Particulate Air Pollution and Hospital Admission for Cardiovascular and Respiratory Diseases. *JAMA* **295**, 1127–1134 (2006).

62. Di, Q. *et al.* Association of Short-term Exposure to Air Pollution With Mortality in Older Adults. *JAMA* **318**, 2446–2456 (2017).

63. Schwartz, J., Fong, K. & Zanobetti, A. A National Multicity Analysis of the Causal Effect of Local Pollution, NO2, and PM2.5 on Mortality. *Environ Health Perspect* **126**, 087004 (2018).

64. Archsmith, J., Heyes, A. & Saberian, S. Air Quality and Error Quantity: Pollution and Performance in a High-Skilled, Quality-Focused Occupation. *J Assoc Environ Resour Econ* **5**, 827–863 (2018).

65. Patel, S. *et al.* Indoor particulate matter during HOMEChem: Concentrations, size distributions, and exposures. *Environ Sci Technol* **54**, 7107–7116 (2020).

66. Zhang, M. *et al.* Indoor airborne particle sources and outdoor haze days effect in urban office areas in Guangzhou. *Environ Res* **154**, 60–65 (2017).

67. International Organization for Standardization. ISO 16890: Air filters for general ventilation. (2016).

68. Ben-David, T., Wang, S., Rackes, A. & Waring, M. S. Measuring the Efficacy of HVAC Particle Filtration over a Range of Ventilation Rates in an Office Building. *Build Environ* **144**, 648–656 (2018).

69. Miller, S. L., Facciola, N. A., Toohey, D. & Zhai, J. Ultrafine and Fine Particulate Matter Inside and Outside of Mechanically Ventilated Buildings. *Int J Environ Res Public Health* **14**, (2017).

70. Luongo, J. C. *et al.* Role of mechanical ventilation in the airborne transmission of infectious agents in buildings. *Indoor Air* **26**, 666–678 (2016).

71. MacNaughton, P. *et al.* Economic, Environmental and Health Implications of Enhanced Ventilation in Office Buildings. *Int J Environ Res Public Health* **12**, 14709–14722 (2015).

72. Wargocki, P., Wyon, D. P., Sundell, J., Clausen, G. & Fanger, P. O. The Effects of Outdoor Air Supply Rate in an Office on Perceived Air Quality, Sick Building Syndrome (SBS) Symptoms and Productivity. *Indoor Air* **10**, 222–236 (2000).

73. Burton, L. E., Girman, J. G. & Womble, S. E. Airborne Particulate Matter within 100 Randomly Selected Office Buildings in the United States (BASE). *Proceedings of Healthy Buildings* **1**, 157–162 (2000).

74. Geng, Y. *et al.* Indoor Environmental Quality of Green Office Buildings in China: Large-Scale and Long-Term Measurement. *Build Environ* **150**, 266–280 (2019).

75. Zheng, T. *et al.* Field evaluation of low-cost particulate matter sensors in high- and low-concentration environments. *Atmos Meas Tech* **11**, 4823–4846 (2018).

76. Nore, P. W. Pollution Detection in a Low-Cost Electronic Nose: A Machine Learning Approach. (University of Oslo, Department of Informatics, 2016).

77. ASTM International Subcommittee E06.41. *Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution*. (2017) doi:10.1520/E0741-11R17.

78. ASTM Subcommittee D22.05. *Standard Guide for Using Indoor Carbon Dioxide Concentrations to Evaluate Indoor Air Quality and Ventilation*. (2018) doi:10.1520/D6245-18.

79. Wood, S. N. *Generalized Additive Models: An Introduction with R*. (Chapman & Hall/CRC, 2006).

80. Lubin, J. H. *et al.* Epidemiologic Evaluation of Measurement Data in the Presence of Detection Limits. *Environ Health Perspect* **112**, 1691–1696 (2004).

81. World Health Organization. *WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide: Global update 2005, Summary of risk assessment*. https://apps.who.int/iris/bitstream/handle/10665/69477/WHO_SDE_PHE_OEH_06.02_eng.pdf?sequence=1 (2006).

82. Zhao, B., Johnston, F. H., Salimi, F., Kurabayashi, M. & Negishi, K. Short-term exposure to ambient fine particulate matter and out-of-hospital cardiac arrest: a nationwide case-crossover study in Japan. *Lancet Planet Health* **4**, e15–e23 (2020).

83. Qiu, Y. & Tang, Y. Investigation of Indoor Air Quality in six office buildings in Chengdu, China based on continuous monitoring data. *IOP Conf Ser: Mater Sci Eng* **609**, (2019).

84. Sangiorgi, G. *et al.* Indoor airborne particle sources and semi-volatile partitioning effect of outdoor fine PM in offices. *Atmos Environ* **65**, 205–214 (2013).

85. Szigeti, T. *et al.* Oxidative potential and chemical composition of PM2.5 in office buildings across Europe – The OFFICAIR study. *Environ Int* **92–93**, 324–333 (2016).

86. Wu, X. (May), Apte, M. G. & Bennett, D. H. Indoor Particle Levels in Small- and Medium-Sized Commercial Buildings in California. *Environ Sci Technol* **46**, 12355–12363 (2012).

87. United States Environmental Protection Agency. Particulate Matter (PM2.5) Trends. https://www.epa.gov/air-trends/particulate-matter-pm25-trends (2020).

88. Lin, Y., Hu, D., Fung, C.-C., Marino, E. & Zhu, Y. Infiltration of diesel exhaust from a loading dock into a nearby building. *Atmos Environ* **216**, 116949 (2019).

89. Pan, L. *et al.* Association Patterns for Size-Fractioned Indoor Particulate Matter and Black Carbon and Autonomic Function Differ between Patients with Chronic Obstructive Pulmonary Disease and Their Healthy Spouses. *Environ Pollut* **236**, 40–48 (2018).

90. United States Green Building Council. LEED v4 for Interior Design and Construction. (2019).

91. International Well Building Institute. The WELL Building Standard - Feature 05: Air Filtration. (2020).

92. Badura, M., Batog, P., Drzeniecka-Osiadacz, A. & Modzel, P. Evaluation of Low-Cost Sensors for Ambient PM2.5 Monitoring. *J Sens* **2018**, 5096540 (2018).

93. Mukherjee, A., Stanton, L. G., Graham, A. R. & Roberts, P. T. Assessing the Utility of Low-Cost Particulate Matter Sensors over a 12-Week Period in the Cuyama Valley of California. *Sensors* **17**, 1805 (2017).

94. Sayahi, T., Butterfield, A. & Kelly, K. E. Long-term field evaluation of the Plantower PMS low-cost particulate matter sensors. *Environ Pollut* **245**, 932–940 (2019).

95. Wang, Z., Delp, W. W. & Singer, B. C. Performance of low-cost indoor air quality monitors for PM2.5 and PM10 from residential sources. *Build Environ* **171**, 106654 (2020).

96. Singer, B. C. & Delp, W. W. Response of consumer and research grade indoor air quality monitors to residential sources of fine particles. *Indoor Air* **28**, 624–639 (2018).

97. Azimi, P., Zhao, D. & Stephens, B. Estimates of HVAC filtration efficiency for fine and ultrafine particles of outdoor origin. *Atmos Environ* **98**, 337–346 (2014).

98. Riley, W. J., McKone, T. E., Lai, A. C. K. & Nazaroff, W. W. Indoor Particulate Matter of Outdoor Origin: Importance of Size-Dependent Removal Mechanisms. *Environ Sci Technol* **36**, 200–207 (2002).

99. Deng, G. *et al.* Indoor/Outdoor Relationship of PM2.5 Concentration in Typical Buildings With and Without Air Cleaning in Beijing. *Indoor Built Environ* **26**, 60–68 (2017).

100. Fisk, W. J., Faulkner, D., Sullivan, D. & Mendell, M. J. Particle Concentrations and Sizes with Normal and High Efficiency Air Filtration in a Sealed Air-Conditioned Office Building. *Aerosol Sci Tech* **32**, 527–544 (2000).

101. Glas, B., Levin, J.-O., Stenberg, B., Stenlund, H. & Sunesson, A.-L. Variability of Personal Chemical Exposure in Eight Office Buildings in Sweden. *J Expo Sci Environ Epidemiol* **14**, S49–S57 (2004).

102. Quang, T. N., He, C., Morawska, L. & Knibbs, L. D. Influence of Ventilation and Filtration on Indoor Particle Concentrations in Urban Office Building. *Atmos Environ* **79**, 41–52 (2013).

103. Smolík, J. *et al.* Indoor Aerosol Particle Deposition in an Empty Office. *Water Air Soil Pollut* **165**, 301–312 (2005).

104. Zuraimi, M. S. & Tham, K. W. Reducing Particle Exposures in a Tropical Office Building using Electrostatic Precipitators. *Build Environ* **44**, 2475–2485 (2009).

105. Ben-David, T. & Waring, M. S. Interplay of Ventilation and Filtration: Differential Analysis of Cost Function Combining Energy Use and Indoor Exposure to PM2.5 and Ozone. *Build Environ* **128**, 320–335 (2018).

106. Kudo, E. *et al.* Low ambient humidity impairs barrier function and innate resistance against influenza infection. *PNAS* **116**, 10905–10910 (2019).

107. Salah, B., Xuan, A. T. D., Fouilladieu, J. L., Lockhart, A. & Regnard, J. Nasal mucociliary transport in healthy subjects is slower when breathing dry air. *Eur Respir J* **1**, 852–855 (1988).

108. Curtis, L., Lieberman, A., Stark, M., Rea, W. & Vetter, M. Adverse Health Effects of Indoor Molds. *J Nutr Environ Med* **14**, 261–274 (2004).

109. Wolkoff, P. Indoor air humidity, air quality, and health – An overview. *International Journal of Hygiene and Environmental Health* **221**, 376–390 (2018).

110. Wolkoff, P. Impact of air velocity, temperature, humidity, and air on long-term voc emissions from building products. *Atmospheric Environment* **32**, 2659–2668 (1998).

111. Kim, J., de Dear, R., Cândido, C., Zhang, H. & Arens, E. Gender differences in office occupant perception of indoor environmental quality (IEQ). *Build Environ* **70**, 245–256 (2013).

112. van Wijk, C. M. T. G. & Kolk, A. M. Sex differences in physical symptoms: The contribution of symptom perception theory. *Soc Sci Med* **45**, 231–246 (1997).

113. Erdmann, C. A. & Apte, M. G. Mucous membrane and lower respiratory building related symptoms in relation to indoor carbon dioxide concentrations in the 100-building BASE dataset. *Indoor Air* **14**, 127–134 (2004).

114. Mendell, M. J. *et al.* Indicators of Moisture and Ventilation System Contamination in U.S. Office Buildings as Risk Factors for Respiratory and Mucous Membrane Symptoms: Analyses of the EPA BASE Data. *J Occup Environ Hyg* **3**, 225–233 (2006).

115. Pejtersen, J., Allermann, L., Kristensen, T. S. & Poulsen, O. M. Indoor climate, psychosocial work environment and symptoms in open-plan offices. *Indoor Air* **16**, 392–401 (2006).

116. Karjalainen, S. Thermal comfort and gender: a literature review. *Indoor Air* **22**, 96–109 (2012).

117. Seppänen, O. & Kurnitski, J. Moisture Control and Ventilation. in *WHO Guidelines for Indoor Air Quality: Dampness and Mould* (World Health Organization, 2009).

118. Larranaga, M. D., Beruvides, M. G., Holder, H. W., Karunasena, E. & Straus, D. C. DOAS & Humidity Control. *ASHRAE J* 34–40 (2008).

119. Taylor, S. H., Scofield, C. M. & Graef, P. T. Improving IEQ To Reduce Transmission Of Airborne Pathogens In Cold Climates. *ASHRAE J* 30–47 (2020).

120. Liu, W., Zhong, W. & Wargocki, P. Performance, Acute Health Symptoms and Physiological Responses during Exposure to High Air Temperature and Carbon Dioxide Concentration. *Build Environ* **114**, 96–105 (2017).

121. Wang, Z. *et al.* Individual difference in thermal comfort: A literature review. *Build Environ* **138**, 181–193 (2018).

122. Pozzebon, J. A., Visser, B. A., Ashton, M. C., Lee, K. & Goldberg, L. R. Psychometric Characteristics of a Public-Domain Self-Report Measure of Vocational Interests: The Oregon Vocational Interest Scales. *J Pers Assess* **92**, 168 (2010).

123. Ceylan, C., Dul, J. & Aytac, S. Can the Office Environment Stimulate a Manager's Creativity? *Hum Factor Ergon Man* **18**, 589–602 (2008).

124. Dul, J., Ceylan, C. & Jaspers, F. Knowledge Workers' Creativity and the Role of the Physical Work Environment. *Hum Resour Manage* **50**, 715–734 (2011).

125. McCoy, J. M. & Evans, G. W. The Potential Role of the Physical Environment in Fostering Creativity. *Creat Res J* **14**, 409–426 (2002).

126. Vohs, K. D., Redden, J. P. & Rahinel, R. Physical Order Produces Healthy Choices, Generosity, and Conventionality, Whereas Disorder Produces Creativity. *Psychol Sci* **24**, 1860–1867 (2013).

127. Lan, L., Hadji, S., Xia, L. & Lian, Z. The effects of light illuminance and correlated color temperature on mood and creativity. *Build Simul* **14**, 463–475 (2021).

128. Witterseh, T., Wyon, D. P. & Clausen, G. The Effects of Moderate Heat Stress and Open-Plan Office Noise Distraction on SBS Symptoms and on the Performance of Office Work. *Indoor Air* **14**, 30–40 (2004).

129. Bolte, A., Goschke, T. & Kuhl, J. Emotion and Intuition: Effects of Positive and Negative Mood on Implicit Judgments of Semantic Coherence. *Psychol Sci* **14**, 416–421 (2003).

130. HOBO Data Loggers. HOBO MX CO2 Logger (MX1102) Manual. (2017).

131. Hofstee, W. K., de Raad, B. & Goldberg, L. R. Integration of the Big Five and Circumplex Approaches to Trait Structure. *J Pers Soc Psychol* **63**, 146–163 (1992).

132. International Personality Item Pool. The Items in the 45 Preliminary IPIP Scales Measuring the 45 AB5C Facets. https://ipip.ori.org/newAB5CKey.htm#Creativity (2018).

133. Watson, D., Clark, L. A. & Tellegen, A. Development and Validation of Brief Measures of Positive and Negative Affect: The PANAS Scales. *J Pers Soc Psychol* **54**, 1063–1070 (1988).

134. International Personality Item Pool. Big-Five Factor Markers. https://ipip.ori.org/newBigFive5broadKey.htm (2018).

135. Goldberg, L. R. The Development of Markers for the Big-Five Factor Structure. *Psychol Assessment* **4**, 26–42 (1992).

136. Stroop, J. R. Studies of Interference in Serial Verbal Reactions. *J Exp Psychol* **18**, 643–662 (1935).

137. Jaeggi, S. M. *et al.* The Relationship between n-back Performance and Matrix Reasoning — Implications for Training and Transfer. *Intelligence* **38**, 625–635 (2010).

138. Kirchner, W. K. Age Differences in Short-Term Retention of rapidly Changing Information. *J Exp Psychol* **55**, 352–358 (1958).

139. Guilford, J. P. The Structure of Intellect. *Psychol Bull* **53**, 267–293 (1956).

140. Bowden, E. M. & Jung-Beeman, M. Normative Data for 144 Compound Remote Associate Problems. *Behav Res Meth Instrum Comput* **35**, 634–639 (2003).

141. Mednick, S. A. The Remote Associates Test. *J Creat Behav* **2**, 213–214 (1968).

142. Guilford, J. P. *The Nature of Human Intelligence*. (McGraw-Hill, 1967).

143. Dippo, C. Evaluating The Alternative Uses Test of Creativity. *P Natl Conf Undergrad Res* (2013).

144. Runco, M. A., Abdulla, A. M., Paek, S. H., Al-Jasim, F. A. & Alsuwaidi, H. N. Which Test of Divergent Thinking Is Best? *Creativity Theories, Research, Applications* **3**, 4–18 (2016).

145. Bowers, K. S., Regehr, G., Balthazard, C. & Parker, K. Intuition in the Context of Discovery. *Cogn Psychol* **22**, 72–110 (1990).

146. Hongyuan, J. *ggpsychro: A 'ggplot2' Extension for Making Pyschrometric Charts*. (2021).

147. Veitch, J. A. & Gifford, R. Choice, Perceived Control, and Performance Decrements in the Physical Environment. *J Environ Psychol* **16**, 269–276 (1996).

148. Gabora, L. Cognitive Mechanisms Underlying the Creative Process. in *Proceedings of the Fourth International Conference on Creativity and Cognition* 126–133 (2002).

149. van Ooijen, A. M. J., van Marken Lichtenbelt, W. D. & Westerterp, K. R. Individual differences in body temperature and the relation to energy expenditure: the influence of mild cold. *J Therm Biol* **26**, 455–459 (2001).

150. Wagner, J. A. & Horvath, S. M. Cardiovascular reactions to cold exposures differ with age and gender. *J Appl Physiol* **58**, 187–192 (1985).

151. Topolinski, S. & Strack, F. The Architecture of Intuition: Fluency and Affect Determine Intuitive Judgments of Semantic and Visual Coherence and Judgments of Grammaticality in Artificial Grammar Learning. *J Exp Psychol Gen* **138**, 39–63 (2009).

152. Geng, Y., Ji, W., Lin, B. & Zhu, Y. The Impact of Thermal Environment on Occupant IEQ Perception and Productivity. *Build Environ* **121**, 158–167 (2017).

153. Kolarik, J., Olesen, B. W., Shitzer, A. & Toftum, J. Occupant Responses and Office Work Performance in Environments with Moderately Drifting Operative Temperatures (RP-1269). *HVAC&R Research* **15**, 931–960 (2009).

154. Zhang, F. *et al.* The Effects of Higher Temperature Setpoints during Summer on Office Workers' Cognitive Load and Thermal Comfort. *Build Environ* **123**, 176–188 (2017).

155. Tanabe, S.-I., Nishihara, N. & Haneda, M. Indoor Temperature, Productivity, and Fatigue in Office Tasks. *HVAC&R Research* **13**, 623–633 (2007).

156. Troyer, A. K., Leach, L. & Strauss, E. Aging and Response Inhibition: Normative Data for the Victoria Stroop Test. *Aging Neuropsychol C* **13**, 20–35 (2006).

157. Zhang, H., Arens, E. & Zhai, Y. A review of the corrective power of personal comfort systems in non-neutral ambient environments. *Build Environ* **91**, 15–41 (2015).