

ABSTRACT

McCORMICK, ELIZABETH L. Contextualizing the Indoor/Outdoor Relationship in Urban American Office Buildings: A Mixed-Methods Study of Cultural Constructs, Occupant Perception, and Air Quality (Under the direction of Dr. Traci Rose Rider).

The footprint of the interior environment is substantial – physically, psychologically, and ecologically – occupying an area nearly equivalent to major ecosystems on the planet’s surface. Humans have effectively become an indoor species. Paradoxically, the quality of indoor air can be significantly worse than outdoor environments, especially regarding airborne chemicals, despite the widespread perception that outdoor air poses a greater risk in American cities. This discrepancy reveals a broader issue: efforts to shield humans from the perceived hazards of the natural world through manufactured environments have led to measurable impacts on human health and well-being. In response, this study advocates for a critical shift toward integration rather than isolation, blurring the boundaries between inside and out.

Because human behavior is inherently complex, understanding evolving perceptions of indoor and outdoor health demands a multidimensional approach. This dissertation employs a mixed-methods, grounded theory framework to examine four urban office spaces in the Southeastern United States (Atlanta, Charlotte, Durham, and Washington DC). Despite high-quality indoor environments, as observed through continuous air quality monitoring and occupant satisfaction surveys, qualitative interviews revealed considerable discontentment among participants regarding time spent indoors during the workday. This dissatisfaction persisted even in offices with access to dedicated outdoor terraces, which were notably underutilized. Many respondents expressed sentiments of feeling “trapped,” “confined,” or as if they were “stuck in a cold box” during the workday, highlighting a disconnect between the observed quality of the indoor environment and occupant experience. While outdoor terraces are widely recognized for promoting employee well-being and workplace satisfaction, these findings reveal that terraces may not fully address the innate human need to connect with nature during the workday.

Exploring the intersection of technological development, air quality, collective expectations, and human behavior in the urban American workplace, this dissertation provides a nuanced understanding of the modern shift toward indoor work since the widespread adoption of

air conditioning in the United States. Using both quantitative and qualitative data within a constructed social history framework, this research aims to provoke the development of future healthy workplace typologies that blend indoor and outdoor environments, highlighting the need for further exploration of specific solutions. By challenging the contemporary boundaries between inside and out, this study offers a unique perspective on the interdependent relationship between humans, nature, and the built environment.

Keywords: sustainable architecture, mechanical ventilation, building facades, airtightness, indoor air quality, workplace design, healthy buildings, outdoor terraces

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Contextualizing the Indoor/Outdoor Relationship in Urban American Office Buildings:
A Mixed-Methods Study of Cultural Constructs, Occupant Perception, and Air Quality

by
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BIOGRAPH

Elizabeth (Liz) McCormick is a licensed architect, educator, and researcher dedicated to advancing healthy, climatically responsive, and contextually appropriate buildings. She is a WELL and LEED Accredited Professional and a Certified Passive House Consultant with over a decade of experience in projects ranging from single-family passive houses to LEED-certified commercial office buildings. McCormick's research work emphasizes strategies that connect occupants to the outdoors while minimizing reliance on mechanical conditioning technologies. Her first book, *Inside OUT: Human Health & the Air-Conditioning Era* (Routledge), published in March 2024, examines the social and technological influences shaping conditioned indoor environments and advocates for thoughtful interventions in the built environment.

As a part-time PhD student, McCormick completed her degree while working full-time as an Assistant Professor of Architecture and Building Technology at the University of North Carolina Charlotte, where her research work has been supported by numerous agencies including the National Science Foundation. In recognition of her contributions to architectural education, McCormick received the 2021 AIAS/ACSA New Faculty Teaching Award. She is also an active member of numerous professional and academic organizations, including the American Institute of Architects (AIA), AIA Charlotte Committee on the Environment (COTE), National Passive House Alliance (PHAUS), and is a board member for the Building Technology Educators Society (BTES) and the Softwood Lumber Board (SLB).

McCormick earned her Master of Science in Building Technology from the Massachusetts Institute of Technology holds a Bachelor of Architecture and Bachelor of Fine Art from the Rhode Island School of Design.

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CHAPTER 1: INTRODUCTION

For the first time in history, humans now occupy a geological epoch driven primarily by anthropogenic activity (Crutzen 2002). This era, known as the *Anthropocene*, is marked by an inseparable relationship between humans and high-density energy - also known as ‘fossil fuels’ - which has irrevocably altered the planet’s trajectory. This relationship is particularly evident in the built environment, where energy-intensive systems create glass-filled skylines that function independently of local climates and regional identities. With urban land at a premium, more energy-intensive, high-rise buildings are being constructed than ever before as global building floor area is expected to double by 2060 (Architecture 2030). The transition from manufacturing to knowledge-based work over the past century has not only driven rapid urban growth but also significantly increased the amount of time people spend indoors (Al Horr et al. 2016). These artificial environments - and their associated health impacts - have emerged as a defining characteristic of the Anthropocene.

Problem Statement

In training the body to “hate the heat,” anthropologist Gwyn Prins identifies the physical addiction to conditioned air as “the most pervasive and least noticed epidemic in modern America” (Prins 1992; Mahdavi and Kumar 1996). Viewed through a deterministic lens, the widespread adoption of air conditioning in the early 20th century fundamentally transformed our relationship with nature. During this period, the view that technology promised a more prosperous future permeated American culture, with the ability to control external forces, such as climate, representing a powerful symbol of human dominion over nature. In the built environment, *manufactured weather* - now referred to as *climate control* - was promoted as a key tenet of modernism that both reinforced and expanded the prevailing notion of absolute human authority (Cooper 2002; Brager and de Dear 2008).

Buildings now function not only as shelters, but as *sanctuaries*, shielding humans – and machines – from the unpredictability of weather and the uncertainties of outdoor air. These factors are shaped equally by cultural influences and physical reality (Böer 2019; Damsky 2003;

Barber 2020; Wierzbicka et al. 2018; Douglas 2002). While these manufactured ecosystems provide refuge, they also give rise to a sense of “weatherlessness,” reflecting a broader psychological emptiness associated with modernism (Stuhr 2019; Pope 2009). This highlights a complex relationship between technology, architecture, and the human experience, suggesting that our sanctuaries may protect us at the cost of deeper connection to the natural world.

From a respiratory health perspective, ambient air pollution has decreased significantly since the introduction of the Clean Air Act in 1970. However, there is no equivalent standard for indoor air quality, which remains largely unregulated in the United States. According to the US Environmental Protection Agency (EPA), the quality of indoor air can be two to five times more polluted than outdoor air, exacerbated by the increased use of synthetic materials that emit harmful contaminants, some of whose effects may not emerge for many years (González-Martín et al. 2021). Additionally, approximately 65% of exposure to outdoor air pollution actually occurs indoors (Fisk 2015). Allergies are rising globally, particularly in developed countries, linked to chemical exposures in low-quality indoor environments (Kim et al. 2013). Furthermore, evidence shows that the notable increase in negative health impacts is linked to environmental exposures rather than genetic changes (Sundell 2004). Despite growing awareness of the risks associated with long-term exposure to unhealthy indoor air, however, most Americans still perceive outdoor air pollution as a more significant threat.

Emerging evidence suggests the need to critically question the relationship between the indoor environment and human health, particularly regarding the stark separation from nature. This project evaluates urban office spaces across the southeastern United States - including Atlanta, Charlotte, Durham, and Washington DC - that exceed industry standards for indoor air quality. The goal is to determine whether these high-quality environments genuinely enhance occupant satisfaction and fulfill their innate desire for a connection with nature, which psychologist Stephen Kaplan aptly describes as, “Not merely ‘nice’” but “is a vital ingredient in healthy human functioning” (Kaplan 1992, 141; cited in Ostner 2021). By integrating historical cultural context with occupant behavior and quantitative metrics of indoor air quality, this work seeks to develop a theoretical framework to provoke innovative workplace typologies – merging the health benefits of the outdoors with the functional demands of indoor settings – without prescribing specific strategies.

Research Questions

This dissertation seeks to contextualize the intricate dynamics between the indoor workplace and human health, emphasizing how physical isolation from nature – despite visual connections – can limit meaningful interactions and negatively impact overall well-being. To navigate these complexities, the following research questions guide the investigation:

RQ1: What social and cultural factors have influenced American perceptions of indoor workplaces since industrialization? What relationships exist between human health, conditioned space, air conditioning, and office work, as constructed through historical literature?

RQ2: How do building occupants utilize outdoor terraces during the workday? Does use of this space satisfy their need to connect with nature in the workplace?

RQ3: How satisfied are occupants of high-quality indoor office environments with their access to nature during the workday? What role do environmental stimuli play in enhancing this connection, and how does it impact occupant's perceptions of indoor health?

The aim is not to dismantle existing assumptions or theories but to clarify the context in which they are applied. Ultimately, this research will examine how theories rooted in social history and technological development can inform the implementation and adoption of architectural change in American office buildings.

Research Approach

The technology-centric approach to sustainable development as the dominant model of innovation in industrialized countries has led to expansive ecological degradation and a growing detachment from nature. Although advanced technologies in buildings aim to mitigate ecological impacts, these systems fail to challenge the deeper issues related to our authoritarian, one-sided relationship with nature. While there are many studies that demonstrate the impact of the built environment on human health, few examine how experiential connections to nature impact occupant *perceptions* of health and well-being. Historically, this experiential issue is viewed as a

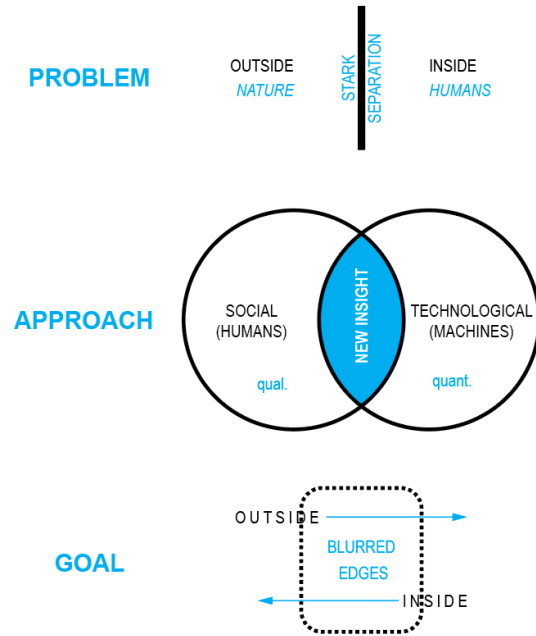


Figure 1, Conceptual Research Diagram

technical problem to be addressed with a strictly technological solution. However, the human relationship with indoor space is complex and cannot be studied through a single method or disciplinary lens. In response, this dissertation uses an interdisciplinary approach to contextualize the intersections between social systems and technical design, shown in Figure 1. This research does not suggest a return to natural conditions and vernacular architecture. Instead, it calls for a deeper connection to the natural environment through design, balancing advanced mechanical technologies with impactful behavioral change.

Given the intricate relationship between people, systems, and the built environment, influenced by a complex interplay of social, economic, cultural, environmental, technological, and behavioral factors, it becomes apparent that mixed-mode research methods are best-suited to explore these interactions within the field of architecture (Aksamija 2021). Under a mixed-methods framework, qualitative and quantitative methods can be well integrated with each other to holistically address complex research questions. Additionally, this research employs a grounded theory approach, which was developed by Glaser and Strauss in 1967 as a technique for systematically analyzing evidence (data) with the intent of creating a theory. Grounded theory is used to “derive a general, abstract theory of a process, action or interaction grounded in the views of the participants” (Creswell and Creswell 2018, 13). Though it is most commonly

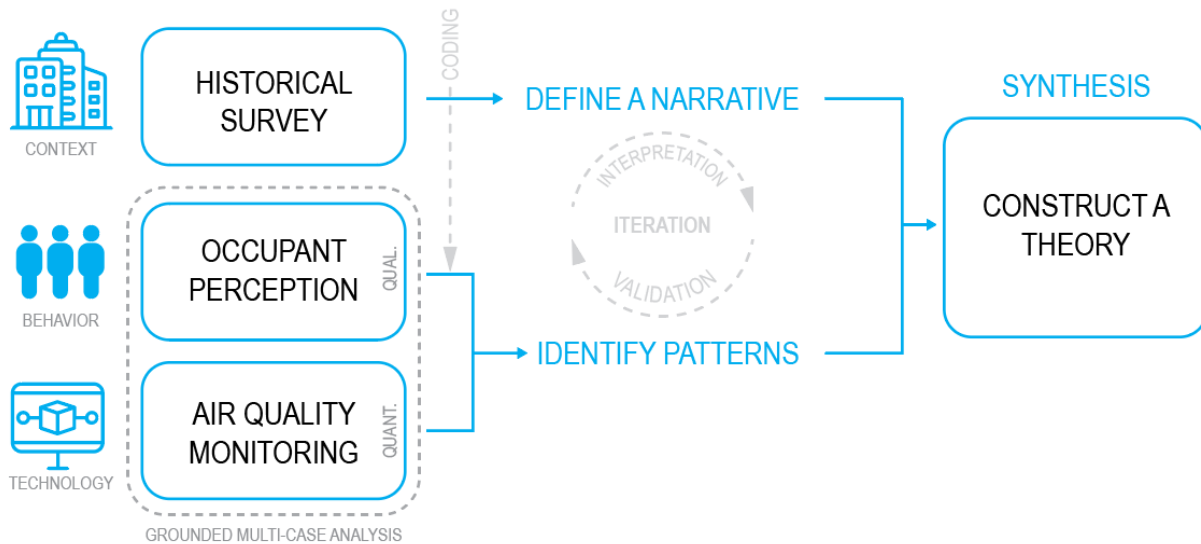


Figure 2, Research Framework

associated with qualitative research, grounded theory can also be used with quantitative methods. In fact, a grounded theory approach appears to be best suited for mixed-methods research in that it requires multiple sources of data to define patterns and establish relationships between categories of information (Bryant and Charmaz 2010). Instead of working through a linear line of inquiry, grounded theory is iterative, requiring the researcher to “double back-and-forth between collecting data, coding them, and memoing” (Groat and Wang 2013, 235). Mixed methods grounded theory (MM-GT), a term coined by Johnson et al. (2010), is used to produce explanatory relationships in contextual settings. Because this research operates between qualitative and quantitative data sets, it identifies and dynamically blends the conflicting demands of the *ideographic* knowledge (contextual) produced by qualitative research and the *nomological* knowledge (universal) produced by quantitative research (Ibid). This dissertation documents the physical metrics of environmental space (quantitative) alongside the human experience (qualitative) – both historical and contemporary – to identify emergent themes.

The methods utilized in this dissertation, shown in Figure 2, were conducted in tandem to inform each other, rather than sequentially, creating a method that is “at least as much about dialogue as about data and analysis” (Bryant and Charmaz 2010, 5). The purpose of this study is to produce a theoretical understanding of blurred edges between inside and out, an analysis that relies on the researchers understanding of both social and technological constructs. The generated theory produces an organization of opportunities and concerns for use in professional

practice so that practitioners can begin to test the theory and shift how urban office buildings are designed.

Study Significance

As people move into cities at unprecedented rates, there is a growing need for healthy urban building typologies deeply rooted in climatic contexts and connected to the natural environment, prioritizing human well-being over mechanical efficiency. In industrialized nations such as the United States, ambient air pollution has gone down significantly since the introduction of the Clean Air Act in 1970. However, poor indoor air quality is still a significant issue, particularly for people who suffer from underlying conditions like allergies and/or asthma, as well as sensitive groups such as children and the elderly. Despite international efforts to combat climate change and improve public health, the continued reliance on mechanical conditioning as the primary thermal strategy in rapidly urbanizing cities poses serious environmental challenges and ongoing threats to human health.

However, addressing health impacts alone is insufficient. We must rethink the prevailing paradigm of sealed office buildings to foster a relationship with nature that promotes synthesis rather than dominion. By redefining our approach to urban architecture, this research seeks to lay the groundwork for a new vernacular aligning human health, environmental sustainability, and our intrinsic connection to the natural world.

Dissertation Organization

This dissertation investigates the complex relationship between indoor environments, air quality, and occupant well-being in US office buildings. It is organized into three standalone articles that synthesize findings from a mixed-methods approach, combining qualitative insights with quantitative metrics to provide a comprehensive understanding of these dynamics.

Article 1: Beyond the Metrics: Exploring the Discrepancy Between Indoor Air Quality and Occupant Satisfaction, Highlighting the Role of Nature in US Office Buildings with Outdoor Terraces. This paper investigates the role of outdoor terraces in urban workplaces, which are intended to foster a connection to nature and enhance employee well-being. While terraces are recognized for their potential benefits, findings reveal a

disconnect between the high-quality indoor environments and participants' feelings of confinement, despite amenities like filtered air and natural light. The study emphasizes that addressing both the physiological and psychological needs of employees requires innovative strategies enhancing sensory experiences and rethinking traditional workplace designs to better support health and satisfaction.

Article 2: Inside Out: Perceptions and Realities of Ambient Pollution and Indoor Air

Quality in Four Office Buildings in the Southeastern US. This paper explores the relationship between perceived and actual air quality, highlighting how many Americans view outdoor air pollution as a greater threat than indoor air quality, despite the health risks associated with poor indoor air. By analyzing indoor and outdoor air quality data along with qualitative feedback from the four office buildings, the study reveals that indoor air is not consistently cleaner or healthier than outdoor air, challenging common assumptions.

Article 3: Climate Controlled: Navigating Perceptions of Weatherlessness in Modern

American Office Buildings. This paper examines how technological advancements and changing health concepts over the past 150 years have transformed the human relationship with nature in contemporary workplaces. By exploring the concept of "weatherlessness" through qualitative interviews in the same four office spaces, this paper illuminates the dynamics of modern work environments.

Together, these papers reveal that while outdoor terraces are intended to enhance employee connection to nature, these spaces often fail to alleviate feelings of confinement experienced by occupants, despite high-quality indoor conditions. Additionally, the research challenges the common perception that indoor air is consistently cleaner than outdoor air, a misconception held by many Americans who tend to view indoor air as a lesser threat. Finally, the dissertation examines how technological advancements and changing health concepts have transformed our relationship with nature, emphasizing the need for innovative workplace designs that address both psychological and physiological needs. Overall, this research calls for a more holistic approach to enhancing health and satisfaction in modern work environments.

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CHAPTER 2: ARTICLE ONE

Beyond the Metrics:

Exploring the Discrepancy Between Indoor Air Quality and Occupant Satisfaction, Highlighting the Role of Nature in US Office Buildings with Outdoor Terraces

Abstract: Outdoor terraces, which are increasingly provided as workplace amenities, aim to provide a direct connection to nature within the confines of urban infrastructure. While such spaces are recognized for promoting employee well-being and workplace satisfaction, findings reveal that they fall short of meeting employees' desire for a deeper connection with nature during the workday. Despite the high standards of the office environments studied - including well-filtered outdoor air, natural light, indoor greenery, and dedicated outdoor terraces - participants expressed sentiments of feeling “trapped,” “confined,” or as if they were “stuck in a cold box” during the workday.

This mixed-methods research examined four urban offices spaces in the US Southeast (Atlanta, Charlotte, Durham, and Washington DC), three of which had outdoor terraces. Data from air quality monitoring, occupant satisfaction surveys, behavior mapping, and semi-structured interviews revealed a notable disconnect between the observed high quality of the indoor environments and participants' dissatisfaction with the amount of time spent indoors during the workday. Despite expressing a strong desire for more outdoor exposure, however, the terrace spaces were rarely used. While the terraces served a valuable social function, they were seldom used for work-related activities due to practical limitations like glare and the absence of necessary desk amenities.

Participants expressed a clear preference for outdoor settings, perceiving them as healthier, particularly for mental health. However, this idealized view of outdoor workspaces was tempered by practical challenges, leading participants to question the feasibility of consistently working outdoors. Ultimately, the study underscores that meeting both the physiological and psychological needs of workers requires more than just optimizing physical environments. It calls for innovative strategies that address sensory experiences and challenge conventional workplace designs, fostering environments that actively support employee health, satisfaction, and well-being.

Introduction

Economic transitions, cultural shifts, and technological innovations of the past century have dramatically increased the amount of time that humans spend indoors, especially in workplace settings. The average American dedicates a staggering 75,000 hours to work, constituting 15% of their adult life¹. While the amount of time spent in any setting can significantly impact an individual's health and well-being, time spent in the workplace is especially impactful because occupants often have limited control over the environment. Environmental determinants, such as lighting, views, and overall interior layout, have a direct and meaningful impact on employee health, satisfaction, and productivity. A workplace with poor environmental quality can also carry substantial economic implications; the impacts of poor indoor air alone cost the United States billions of dollars a year in lost productivity and medical expenses (Awada et al. 2021). The COVID-19 pandemic, in particular, highlighted the profound impact of contemporary interior spaces on human health. As a result, the focus has shifted from simply 'transitioning back' to the office to reevaluating traditional workplace environments and employers are now placing greater emphasis on the health and wellness implications of the workplace.

The evolving character of work environments is characterized by increased flexibility and a departure from traditional office settings, which complicates our understanding of workplace boundaries (Pettersson Troije et al. 2021). Incorporating natural elements, whether through biophilic design, access to outdoor terraces, or the presence of natural light, can foster a deeper connection to the natural world. In doing so, workplaces can help mitigate the negative effects of spending extended time indoors and provide employees with both the psychological and physiological benefits that nature offers (Park et al. 2010; Ostner 2021; Fitzgerald and Danner 2012; Bratman et al. 2019). As many employees have found these amenities more accessible in remote and hybrid work environments, adapting traditional office norms to meet the need for a deeper connection with nature becomes not just a matter of preference, but a necessity for supporting well-being, promoting workplace satisfaction, and driving productivity.

¹ Assuming that Americans begin working full time at 20 years old at the average rate of 1,811 hours per year (OECD 2024) and the average retirement age of 61 (Gallup 2022; Jones 2022) with an average life expectancy of 76.4 years (Xu et al. 2022).

The newfound prioritization of outdoor space in the workplace is not only a response to the health challenges posed by the COVID-19 pandemic but also reflects a deliberate effort to harness the therapeutic benefits associated with exposure to nature (Rishi et al. 2021). While some building owners and employers provide outdoor terraces and natural features as an amenity, research suggests that access to nature in the workplace is actually a fundamental human need, not a luxury. As psychologist Stephen Kaplan aptly stated,

Nature is not merely 'nice'. It is not just a matter of improving one's mood, rather it is a vital ingredient in healthy human functioning (Kaplan 1992, 141; cited in Ostner 2021).

However, the relationship between humans and nature within workplace settings is inherently nuanced. This paper aims to illuminate some of the complexities of this dynamic, drawing insights from a mixed-method research study of four distinct office spaces in the US Southeast, three of which provide access to dedicated outdoor terraces. Despite having access to high-quality indoor air, daylight, indoor plants, and outdoor terraces, building occupants expressed a clear interest in a deeper connection with nature during the workday. These findings reveal that while these natural amenities offer significant value, they fall short in fulfilling the intrinsic human need for a meaningful connection with nature. By closely examining current trends, challenges, and the untapped potential of integrating outdoor spaces into the work environment, this paper argues for a deeper, more strategic approach to workplace design. To truly support the well-being and productivity of the 21st-century workforce, it is imperative to rethink workplace designs to more effectively blur the line between indoor and outdoor environments.

Background

In recent years, the understanding of how indoor environments impact human health and wellness has evolved significantly. The COVID-19 pandemic has served as a much-needed catalyst, accelerating shifts in workplace dynamics geared toward greater flexibility and a move away from the traditional office model. This transformation has sparked a critical reassessment of modern workplace design, particularly as technological advancements and the prevalence of sealed indoor spaces have become more common. As organizations seek to create healthier work environments, there is a growing focus on integrating elements that enhance well-being, such as

biophilic design, access to outdoor terraces, and improved air quality. This section explores ongoing efforts to optimize workplace environments for health and productivity, highlighting initiatives like the WELL Building Standard, which aim to set benchmarks for creating spaces that support both physical and mental well-being.

A. Biophilia

The *biophilia hypothesis*, introduced by American biologist Edward O. Wilson in 1984, speculates that humans have an innate and genetic need to connect with nature (Wilson 1984), influencing everything from mental well-being to physical health and overall quality of life (Ostner 2021). While a direct connection with nature may not always be possible in urban settings, biophilic design seeks to integrate natural elements into the built environment. This design philosophy suggests that humans respond positively to nature and that a more ‘natural’ building can elicit positive responses with a direct influence on occupants’ well-being (Ulrich 1995). Biophilic design principles emphasize incorporating elements such as natural light, vegetation, and natural materials into buildings, resulting in both psychological and physiological benefits (Joye 2007).

The inclusion of indoor plants, for example, has demonstrated a positive influence on the overall well-being of building occupants, resulting in fewer health complaints and reduced sick leave (Han and Ruan 2019; Bringslimark et al. 2007). Similarly, research indicates a clear correlation between visual factors, such as daylight and views, and thermal perceptions within a space (Chinazzo et al. 2019; te Kulve et al. 2018). Exposure to natural light not only enhances visual comfort but also regulates circadian rhythms, promoting a sense of alertness during the day and better sleep quality at night. Similarly, in a 2020 study, Ko et al. demonstrated that windows providing a visual connection to the outdoors had a cooling effect, with 12% of participants reporting feeling more comfortable, despite similar thermal conditions to the room without windows. Their analysis revealed that having a window translated to a cooling effect of $.74^{\circ}\text{C}$ (1.33°F), leading to potential energy savings in buildings (Ko et al. 2020). Additionally, visual connection to nature has been shown to positively impact attention, stress levels, discomfort, and overall health and well-being (Aries et al. 2010; Leather et al. 1998). Individual psychological adaptations, however, such as expectations for ‘naturalness,’ duration of exposure,

perceived control, and environmental stimulation, can also influence biophilia-related comfort perceptions (Nikolopoulou and Steemers 2003). Importantly, the concept of biophilia extends beyond mere aesthetics, aiming to acknowledge the profound connection humans have with nature by encouraging active engagement with natural elements throughout the day.

B. Outdoor terraces

In a 2019 New York Times article, journalist Jane Margolies asserts that outdoor work areas are a logical progression in the evolution of flexible offices, emphasizing the growing recognition of the importance of nature in the workplace (Margolies 2019). Outdoor terraces can be used to facilitate a more direct and immersive interaction with nature within the confines of urban infrastructure. The significance of this approach is reflected in a 2019 report by CBRE, a global commercial real estate services and investment firm, indicating that floors with terraces command a 14% higher rent than those without outdoor access (Cuozzo 2019).

One relevant example is the 11-story office building at 512 W. 22nd St. in New York City (CookFox 2017), with nearly 17,000 SF of planted terraces and a common roof. Inspired by the principles of biophilic design, every floor in the building features operable windows and direct access to planted outdoor space, a deliberate endeavor aimed at fostering a deep connection between building occupants and the natural world (Weiss 2016). CookFox has their own office space in the building, and their outdoor space is used to keep bees and grow kale. Across the country, HOK unveiled the Center for Academic Medicine at Stanford University in Palo Alto (2021). Focused on addressing occupant mental health through biophilia design principles, 20% of programmed activities, including both work and leisure spaces, were relocated to outdoor spaces. Leveraging Northern California's mild climate, the design team employed a "passive-first design approach," incorporating balconies, skybridges, and covered walkways to reduce energy consumption by 85% from baseline. The design's attention to biophilic design principles aimed not only to mitigate environmental impact but also to address the pressing issue of physical burnout.

C. Air quality

Air movement has been used throughout history as a simple yet effective strategy for managing indoor thermal comfort, as the flow of air can significantly influence how occupants perceive indoor thermal conditions (Schiavon and Melikov 2008; Shuo Liu et al. 2018; Arens et al. 2009). Furthermore, building occupants frequently prefer natural ventilation over mechanical alternatives, primarily because it fosters a deeper connection with nature (Sijing Liu et al. 2022; Brager and de Dear 1998). Natural ventilation offers a direct connection to outdoor air, enabling occupants to experience natural sounds, scents, and occasional breezes. This direct link to nature has been shown to positively affect mental well-being and enhance overall indoor comfort. As a result, outdoor air is often perceived as ‘fresher’ than air circulated through mechanical systems (Gao et al. 2014). Additionally, natural ventilation provides variable airflow that adapts to outdoor conditions, in contrast to the consistent, controlled airflow of mechanical systems. When occupants anticipate greater temperature variations outdoors, they are generally more willing to tolerate a wider range of thermal conditions with naturally-conditioned air (Tan et al. 2019).

Although building occupants frequently prefer natural ventilation, most American office buildings continue to rely on mechanical systems for regulating temperature and airflow, however indoor air pollution remains largely unregulated in the United States. The organization that promotes healthy and safe working conditions in the United States, the Occupational Safety and Health Administration (OSHA), does not set standards for indoor contaminants, however, it does regulate ventilation rates similar to the American Society for Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), which is a professional organization that produces a variety of standards used within the building industry. ASHRAE Standard 62, Ventilation for Acceptable Indoor Air Quality, is the predominant standard used in the United States to regulate building ventilation rates (Persily 2015). Though ASHRAE Standards do specify minimum acceptable fresh-air ventilation rates, there is no set limit for indoor contaminants, including indoor carbon dioxide (CO₂). Though CO₂ is not necessarily a respiratory threat, it can serve as a proxy for other air quality or ventilation issues. Instead, ASHRAE believes that “indoor CO₂ concentrations of 1000 to 1200 ppm in spaces housing sedentary people is an indicator that a substantial majority of visitors entering the space will be satisfied with respect to human

bioeffluents (body odor)”². However, recent studies show that higher CO₂ levels, particularly above 900 ppm are associated with decreased cognitive function in adults (Laurent et al. 2021; Allen et al. 2016).

Allen et al.’s Cognitive Function (COGfx) study provides compelling evidence that enhanced ventilation rates of at least 40 cubic feet per minute (CFM) per person and low indoor pollutant levels can enhance adult cognitive function by up to 101% beyond baseline conditions. Even in environments with a reduced ventilation rate of 20 CFM per person, participants exhibited a notable improvement of 61% in cognitive performance when exposed to low pollutant levels (Allen et al. 2016). A follow-up study found that providing enhanced ventilation at a rate of 40 CFM per person would cost less than \$40 per person per year but improve employee performance by 8% (MacNaughton et al. 2015). These findings underscore the significant potential of optimized ventilation strategies not only for fostering healthier indoor environments but also for enhancing cognitive functions and productivity in the workplace.

While ambient (outdoor) air pollution has significantly decreased in the United States since the introduction of the Clean Air Act in 1970, the quality of indoor air poses an entirely unique and often underestimated threat, particularly with the increased use of synthetic materials in buildings. These materials emit contaminants indoors, some of which are still unknown as the effects may not emerge for many years (González-Martín et al. 2021). Approximately 65% of exposure to outdoor air pollution actually occurs indoors (Fisk 2015). In response, researchers of the indoor environment are increasingly focused on ozone (O₃), particulate matter (PM_{2.5} and PM₁₀), and total volatile organic compounds (tVOC). While ozone and particulate matter usually come from outdoor sources like vehicle emissions and industrial activities, tVOCs typically originate from indoor sources such as cleaning supplies, building materials, and furnishings. A growing body of evidence suggests that the significant increase in health impacts, such as asthma and allergies, in developed countries is likely due to chemical exposures from low-quality air in buildings (Sundell 2004).

² ASHRAE also notes that CO₂ concentration is “not a good indicator of the concentration and occupant acceptance of other indoor contaminants, such as volatile organic compounds off-gassing from furnishings and building materials. Thus, CO₂ concentration is not a reliable indicator of overall building air quality.” (ASHRAE Technical FAQ, ID35)

D. Green building standards and industry trends

LEED (introduced in 1998) and the WELL Building Standard (introduced in 2013) are two international green building organizations that are trying to address the concerns associated with indoor air quality, though the requirements are still voluntary. While LEED is a more general program focused on overall sustainability, WELL is specifically geared toward health and wellness. Both LEED (v4.1) and WELL (v2) mandate a certain level of air quality performance as prerequisite criteria in addition to cigarette smoke control. With the intent of “contribut[ing] to the comfort and well-being of all building occupants by establishing minimum standards for indoor air quality (IAQ),” LEED v4.1 Indoor Environmental Quality (EQ) Prerequisite states,

For mechanically ventilated spaces, meet the requirements of ASHRAE Standard 62.1-2016, Sections 4 [outdoor air quality], 5 [systems and equipment], 6.2 [ventilation rate procedure], 6.5 [exhaust ventilation], and 7 [construction and system startup], or a local equivalent, whichever is more stringent AND provide outdoor air monitors for all mechanical ventilation systems with outdoor air intake flow greater than 1000 cfm (472 L/s) (LEED v4.1 2024).

Generally, LEED air quality guidance is established by ventilation rates and does not require any monitoring of individual contaminants aside from carbon monoxide in residential dwellings. In contrast, WELL certified projects must actively monitor indoor air to maintain contamination levels below certain thresholds for particulate matter (PM_{2.5} and PM₁₀), organic gases such as benzene, formaldehyde, and toluene, which can also be achieved by monitoring VOC’s, inorganic gases such as carbon monoxide and ozone, and radon. These pollutants must be monitored in regularly occupied spaces and submitted through the WELL digital platform yearly. According to the standard,

The WELL Air concept aims to ensure high levels of indoor air quality across a building’s lifetime through diverse strategies that include source elimination or reduction, active and passive building design and operation strategies and human behavior interventions (WELL v2 2020).

Additional Air Concept credits are offered for enhanced ventilation, operable windows, air quality monitoring and awareness, and pollution infiltration management.

While LEED v4 does not reference biophilia by name, it does call for daylight, views, water features, and other natural features. LEED v4 Building Design and Construction (BD+C)

for healthcare offers credits for providing places of respite “to provide patients, all staff, and visitors with the health benefits of the natural environment by creating outdoor places of respite on the healthcare campus,” which must be equal to 5% of the *net usable program area* of the building for patients and visitors and 2% dedicated place of respite for staff. No medical care can be delivered within this area. LEED v5, which is currently under development and review, plans to include prerequisites and supplementary credits that specifically address biophilic design.

WELL v2 speaks more directly to the features of biophilic design, including circadian lighting design (WELL feature L03), and enhanced access to nature (WELL feature M09). WELL also has two features for biophilia, 88: Biophilia I (qualitative) and 100: Biophilia II (quantitative). The first, feature 88, requires a ‘biophilia plan’ describing how the project incorporates nature through environmental elements, lighting, and space layout. It also describes sufficient opportunities for human-nature interactions within the building, as well as external to the building (within the project boundary). Feature 100 requires a landscaped ground or rooftop garden accessible to building occupants, indoor potted plants, and water features. These standards reflect a growing recognition of the importance of integrating nature into indoor spaces for the health and well-being of occupants.

E. Summary

The evolving understanding of how indoor environments impact human health and wellness has led to a significant shift in modern workplace design paradigms, accelerated by the COVID-19 pandemic. The integration of biophilic design principles, such as incorporating natural elements and providing access to outdoor spaces, is increasingly recognized as essential for promoting well-being and enhancing productivity. Efforts to improve air quality through optimized ventilation and contaminant monitoring are also critical, as evidenced by the limitations of current regulations and the growing focus of evidence-based standards like LEED and WELL. These developments underscore a broader trend toward creating workspaces that not only address immediate health concerns but also foster a deeper, more meaningful connection with nature. As we continue to navigate these changes, it is clear that a holistic approach to indoor environmental quality – one that balances natural and technological elements – will be vital in shaping healthier and more productive workplaces.

Methods

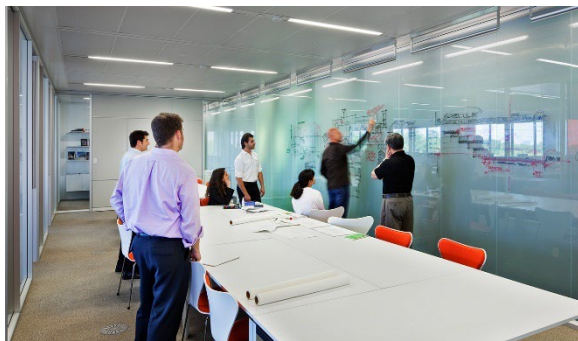
Considering the intricate relationships between people, systems, and the built environment, which are shaped by the complex interplay of social, economic, cultural, environmental, technological, and behavioral factors, this study adopts a mixed-method research approach, which is most effective for studying such dynamics in architecture (Aksamija 2021). Additionally, the study utilizes a grounded theory approach, which was developed by Glaser and Strauss in 1967 as a technique for systematically analyzing evidence (data) with the intent of creating a theory “grounded in the views of the participants” (Creswell and Creswell 2018, 13). Although it is most commonly attributed with qualitative research, grounded theory can also be used in quantitative methods and is particularly effective in mixed-methods research in that it requires multiple sources of data to identify patterns and establish relationships between different categories of information (Bryant and Charmaz 2010). Instead of following a linear line of inquiry, grounded theory is iterative, requiring the researcher to move between collecting and analyzing data (Groat and Wang 2013). This iterative process ensures a deeper and more nuanced understanding of the research subject, allowing for the development of theories that closely align with multiple sources of data.

This study extended over an eleven-month period, with continuous indoor air quality monitoring of four unique office spaces throughout the year. Focused study periods occurred once per season, each lasting two weeks. Semi-structured interviews were conducted with building occupants during the fall and spring study periods, though the outcomes of the second round of interviews will be addressed in a separate paper. Occupant satisfaction surveys were also administered during the winter and summer study periods. Additionally, behavior monitoring was conducted during each season to understand patterns of outdoor terrace usage. Study procedures were approved by the North Carolina State University Institutional Review Board (IRB #25686). Further elaboration on each of these methodologies, as well as detailed insights into the building under examination, are described in more detail below.

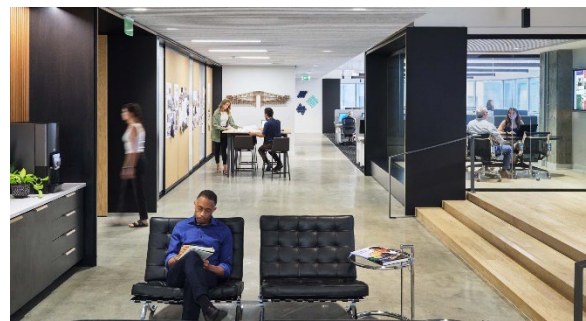
A. Study buildings

This research focuses on commercial office buildings in large metropolitan areas in the US Southeast, including Atlanta, Charlotte, Durham, and Washington DC. The climate of the US

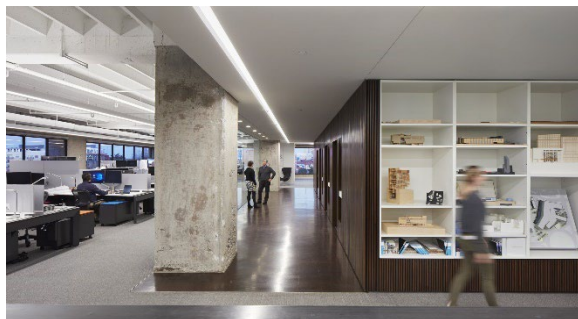
Southeast is characterized as humid and subtropical, with moderate winters and hot-humid summers. It spans ASHRAE climates zones 3A in Atlanta and Charlotte, and 4A in Durham and Washington DC. Although each of the four offices functions independently, they are part of the same international architectural design practice specializing in sustainable building design across 28 offices around the world. Each of the study offices was designed by the occupant firm with both health and building performance in mind, including expansive glazing with views of the city, indoor vegetation, and low emitting materials.



Atlanta Office



Charlotte Office



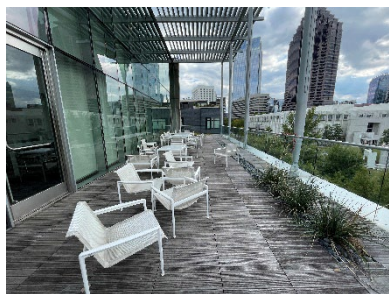
Durham Office



Washington DC Office

Figure 1, Study Locations

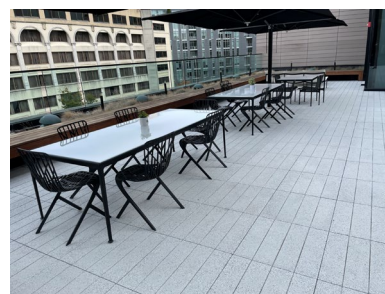
The office sizes and occupancy levels vary significantly across locations, shown in Figure 1. The Atlanta office is the largest, spanning 31,500 square feet (SF) and accommodating 175 employees across two floors connected by an atrium. In contrast, The Charlotte office is the smallest, covering 7,500 SF with 25 employees. The Durham office is slightly larger in area than Charlotte, with just over 11,000 SF but also housing 25 employees. Notably, the Durham and Charlotte offices function as a single practice with shared leadership. The Washington DC office



Atlanta Office, 5th Floor



Charlotte Office, 5th Floor



Washington DC Office, Roof (5th floor)

Figure 2, Workplace Terraces

occupies roughly 14,300 SF and hosts 65 employees. These variations in office size and occupancy offer a diverse set of environments for exploring the impacts of space on employee experience and organizational dynamics, all within the same parent company and under the same policies. Additionally, the Atlanta and Charlotte locations offer dedicated outdoor terraces directly accessed from the workspace, shown in Figure 2. The Washington DC office has a rooftop terrace three floors up shared with other tenants in the building.

The HVAC systems at the Charlotte, Durham, and Washington DC offices are conventional variable air volume (VAV) systems. These systems regulate the airflow to different zones based on current heating and cooling needs, maintaining a consistent indoor environment while optimizing energy use. Following a 7-million-dollar HVAC upgrade in 2021, the Durham office now utilizes an economizer to provide 100% outdoor air when conditions are favorable. This component allows the system to leverage outdoor air for cooling, reducing the need for mechanical cooling and potentially improving air quality. In cases where outdoor conditions are less favorable, the system provides a minimum of 30% outdoor air to ensure that there is always fresh air circulating within the building. Additionally, the building's central air handling system is equipped with an ionization system claiming to purify the air by reducing particulate matter, allergens, and VOCs in the indoor environment. In Washington DC, the fresh air distribution system is designed to react to indoor CO₂ levels by supplying additional outdoor air if indoor CO₂ levels exceed 600 ppm. This approach ensures that indoor air quality remains optimal while managing heating and cooling loads, as outdoor air is provided at the ASHRAE minimum rate of 5 CFM/person.

Of the buildings under study, the Atlanta office stands out due to its unique ventilation system. Fresh air is supplied independently of thermal controls through a rooftop dedicated outdoor air system (DOAS) equipped with energy recovery. This system ensures a continuous

supply of fresh air to ensure proper ventilation and removal of indoor air pollutants. During the winter, however, a damper on Atlanta's DOAS closed as a precaution against freezing temperatures. As the building relies on a radiant system for heating and cooling, fresh air was not supplied during this time, leading to uncharacteristically poor indoor air quality, during the winter study period. This incident highlights a significant failure in building operations, attributed to the hiring of a new building manager with limited knowledge of radiant systems. The manager was unaware that the damper status required regular inspection, an issue that went unnoticed until occupants complained of stuffy conditions and uncomfortable temperatures in March. Due to this anomaly, data from the winter study in the Atlanta office have been excluded from the overall results.

B. Air quality monitoring

Indoor air quality (IAQ) data was recorded by multiple Kaiterra Sensedge Mini sensors in each office, logging PM_{2.5}, PM₁₀, tVOC, CO₂, temperature, and relative humidity, on 15-minute intervals. Data was collected continuously for eleven months, spanning fall 2023 – 2024. To the extent possible, the study followed the Performance Verification protocol for sensor data established by the WELL Building Standard (IWBI 2022). Sensors were installed vertically within the breathing zone (3.6 – 5.6 ft AFF), at least 3.3 ft away from walls, doors, windows, air supply/exhaust outlets, air purifiers, or other potential influences. WELL protocol requires one sensor per 3,500 square feet, with a minimum of two sensors for spaces smaller than 35,000 square feet. Due to the high cost of equipment, only the minimum of two sensors was installed at each location - one in the primary work area and the other in the communal kitchen. The exception is the Washington DC studio which already had four sensors installed, including additional sensors in the entryway and main conference room. Live data was accessible to building occupants at each location through an online dashboard provided on the Kaiterra website. This dashboard displayed real-time indoor air quality values and categorized both indoor and outdoor air as good, moderate, or poor. Sensors were validated at the beginning and end of the study in accordance with the manufacturer guidelines.

C. Behavior Mapping

Behavior mapping was performed over two-week periods in each season in the Atlanta, Charlotte, and Washington DC offices. During each of these four periods, occupants were instructed to scan a QR code whenever they used the outdoor terrace and respond to a brief survey. The survey, administered through Qualtrics, posed two questions: “Why did you move outside?” and “What type of activity are you doing outside?” The survey automatically collected the date and time of each response, enabling precise identification of the corresponding indoor and outdoor environmental conditions at the time of the survey. Participant identities and personal information were not collected.

QR codes were placed on potted plants in the Charlotte and Atlanta terraces, as shown in Figure 3. During non-study periods, these plants were stored in a separate location. The Washington DC office encountered specific challenges as the shared outdoor terrace, which was managed by an external entity, did not permit the placement of potted plants or QR codes. Instead, a flyer was placed next to the elevators, shown in Figure 4, instructing participants to scan it before accessing the terrace. The behavior mapping process faced several challenges, which may have affected the accuracy of the data on terrace usage. Participation in the QR code survey was voluntary, making it difficult to know the total number of individuals using the terrace who did not engage with the survey. Participation is shown in table 1, for a total of 40 responses.



Figure 3, Atlanta QR location

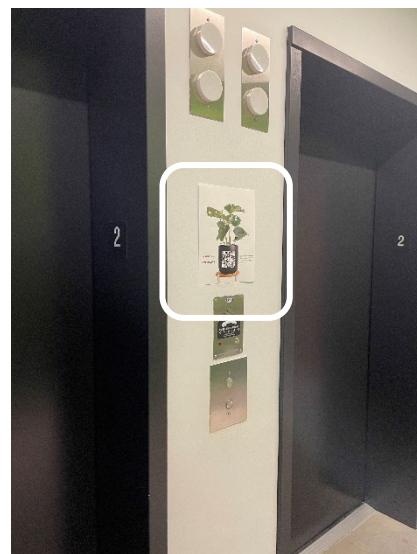


Figure 4, Washington DC QR location

Table 1, participation in QR surveys at each location

| | Fall | Winter | Spring | Summer | TOTAL (site) |
|--------------------------|----------|----------|-----------|-----------|--------------|
| Atlanta | 0 | 3 | 8 | 13 | 24 |
| Charlotte | 2 | 0 | 3 | 0 | 5 |
| Washington DC | 1 | 0 | 8 | 2 | 11 |
| Total (by season) | 3 | 3 | 19 | 15 | 40 |

Table 2, Number of survey responses and interview participation at each location (% participation of full staff)

| | # of Staff | Survey Participation | | Interview Participation | |
|----------------------|------------|----------------------|-----------------|-------------------------|----------------------|
| | | Winter | Summer | Fall (Questions A) | Spring (Questions B) |
| Atlanta | 175 | 11 (6%) | 20 (11%) | 2 (1%) | 5 (3%) |
| Charlotte | 25 | 10 (40%) | 7 (28%) | 6 (24%) | 5 (20%) |
| Durham | 25 | 7 (28%) | 4 (16%) | 6 (24%) | 7 (28%) |
| Washington DC | 65 | 10 (15%) | 3 (5%) | 4 (6%) | 3 (5%) |
| Total | 340 | 38 (11%) | 34 (10%) | 18 (5%) | 20 (6%) |

D. Occupant satisfaction surveys

Post-occupancy evaluations (POEs) are a common tool used to evaluate the occupant experience and the success of a built design. Occupants were invited to participate in a short, online surveys in both winter and summer, in line with WELL protocol. The core of the survey was based on the UC Berkeley Center for Built Environment (CBE) Occupant Satisfaction Survey, a tool that has been in use for over 20 years and implemented in over 1,000 buildings worldwide (Graham 2021). Additional questions were added to assess occupant satisfaction with the available outdoor terraces. The survey was used to identify common sources of occupant dissatisfaction to understand conditions where occupants might choose to use the outdoor space. Published CBE data are used to add context to survey responses from this study and determine how the test locations compare to other commercial buildings in North America (Parkinson et al. 2023; Kent et al. 2024). An average of 10.5% of employees participated in the survey with particularly high engagement from Charlotte and Durham and low engagement from the Atlanta and Washington DC offices. Participation ratios are shown more clearly in Table 2.

E. Semi-structured interviews

Employees were invited to participate in semi-structured interviews through emails distributed by an internal point of contact and postcard announcements placed on each desk at the start of each study period. Participation was voluntary, and company leadership had no direct influence on who chose to participate. Each site was offered two opportunities to participate in interviews during the fall and spring research periods – once in person and once remotely via Zoom. Participants could sign up for 20-minute interview slots on designated days using the Calendly online scheduling tool. Consent was obtained from each interviewee, and all interviews were audio-recorded for transcription purposes. Interviews were semi-structured, beginning with a uniform series of fourteen questions aimed at understanding the employee’s experience and perceptions of their workplace environment, particularly the physical space and access to the outdoors. The full list of questions can be found in the Appendix B.

Table 3. Themes and Codes: Satisfaction with the environment

| Sensory Factors | Urban Environment | Access to Nature | Office Features | Health |
|------------------------|-------------------------------|--|-----------------------------|-------------------------------|
| <i>Acoustics</i> | <i>Connection to the city</i> | <i>Biophilia/plants</i> | <i>Diversity of spaces</i> | <i>Allergies/asthma</i> |
| <i>Lighting/glare</i> | <i>Commute</i> | <i>Environmental cues/ changes/rhythms</i> | <i>Flexibility/mobility</i> | <i>Mental health</i> |
| <i>Fresh air</i> | <i>Air pollution</i> | <i>Views of nature</i> | <i>Furniture/technology</i> | <i>Productivity/happiness</i> |
| <i>Temp./humidity</i> | <i>Urban noise</i> | <i>Naturalness</i> | | |
| <i>Comfort</i> | | <i>Ephemeral qualities</i> | | |

Table 4. Themes and Codes: Relationship with the outdoors

| Activities | Mental Rest | Deterrents |
|--------------------|--------------------------------|---------------------|
| <i>Eating</i> | <i>Refocus/shift mindset</i> | <i>Choice</i> |
| <i>Socializing</i> | <i>Retreat/respice</i> | <i>Habits</i> |
| <i>Working</i> | <i>Take a break</i> | <i>Access</i> |
| | <i>“Thaw out”</i> | <i>Control</i> |
| | <i>Change of scenery</i> | <i>Work culture</i> |
| | <i>Preference for outdoors</i> | |

Each interview transcript was subjected to a process of open coding, which involved a meticulous line-by-line analysis in the Dedoose qualitative research tool. A grounded theory approach was used for data analysis, allowing themes to emerge organically from the data (Corbin and Strauss 2008). Once the transcripts were analyzed and coded, emergent thematic

codes were established to describe the categories and subcategories established from patterns in the transcripts, providing a framework to recognize recurrent ideas and concepts (Charmaz 2006). This iterative process was used to provide a systematic and meaningful representation of the interview data and was instrumental in uncovering key insights, connections, and overarching concepts inherent in the participants' responses. Those themes (in bold) and codes (in italics) are shown in Tables 3 and 4 below.

Results

This paper focuses on the difference between measured air quality and occupant perceptions of air quality, questioning whether outdoor terraces satisfy the inherent human desire for a connection to nature. The analysis begins with a review of the quantitative air quality data, contextualized within established air quality targets. Once the actual air quality is established, occupant interviews are discussed in relation to the air quality measurements.

A. Indoor air quality

Though none of the offices are currently pursuing WELL certification, measured data from each space was evaluated against WELL v2 criteria to provide valuable context and insights. This data is summarized in Table 5. In this evaluation, CO₂, while not classified as a particularly potent air contaminant, was used as a key indicator of ventilation efficiency, reflecting the amount of fresh air circulating in a space. Across all four offices, average CO₂ concentrations during working hours (8 am – 6 pm) remained well below the acceptable condition established by ASHRAE at 1000 ppm. Additionally, average conditions in all four offices complied with the WELL v2 prerequisite for A03 Ventilation Design (option 4, ventilation monitoring), which requires CO₂ levels of 900 ppm or less, or not more than 500 ppm above outdoor levels (A03 Ventilation Design 2024). Figure 5 illustrates the average conditions across the four seasonal study periods. CO₂ levels closely correlate with occupancy, and the rapid dissipation of CO₂ concentrations during non-working hours indicates that each space is well ventilated. This data also highlights occupancy trends, with many employees working in the office for only three days

a week and working remotely on the remaining days. Notably, CO₂ concentrations were lower on Mondays and Fridays across all four offices, reflecting reduced in-office presence on those days.

During working hours, the average CO₂ conditions were 571 ppm in Atlanta, 511 ppm in Charlotte, 450 ppm in Durham, and 515 ppm in Washington DC, which are all below the baseline CO₂ concentrations of 578 ppm observed in the Americas (Canada, Peru, Puerto Rico, and the United States) and 583 ppm observed globally (Kaiterra 2023). Notably, only the average CO₂ in the Atlanta office exceeded the more stringent thresholds outlined by Allen et al. (2016), which indicates that cognitive function declines when interior CO₂ levels exceed 550 ppm. While the Atlanta and Washington DC offices exhibited generally low average conditions, there were sporadic instances of CO₂ levels exceeding 900 ppm, which would need attention if pursuing WELL certification. Nonetheless, the overall CO₂ levels suggest efficient design and management of ventilation systems with a significant exchange of outdoor air within all four study offices.

Despite excellent ventilation practices and the company’s commitment to using low-emitting materials, each of the sites experienced challenges in managing peaks in tVOC concentrations, indicating issues related to interior sources. Although all four offices exceeded the WELL prerequisite threshold of 500 µg/m³, their levels remained significantly below the average concentrations reported in Kaiterra’s study, which found that buildings in the Americas averaged at 6,050.7 µg/m³ during working hours, which Kaiterra categorizes as ‘poor’. The average tVOC concentrations in Charlotte and Durham only slightly exceeded the WELL

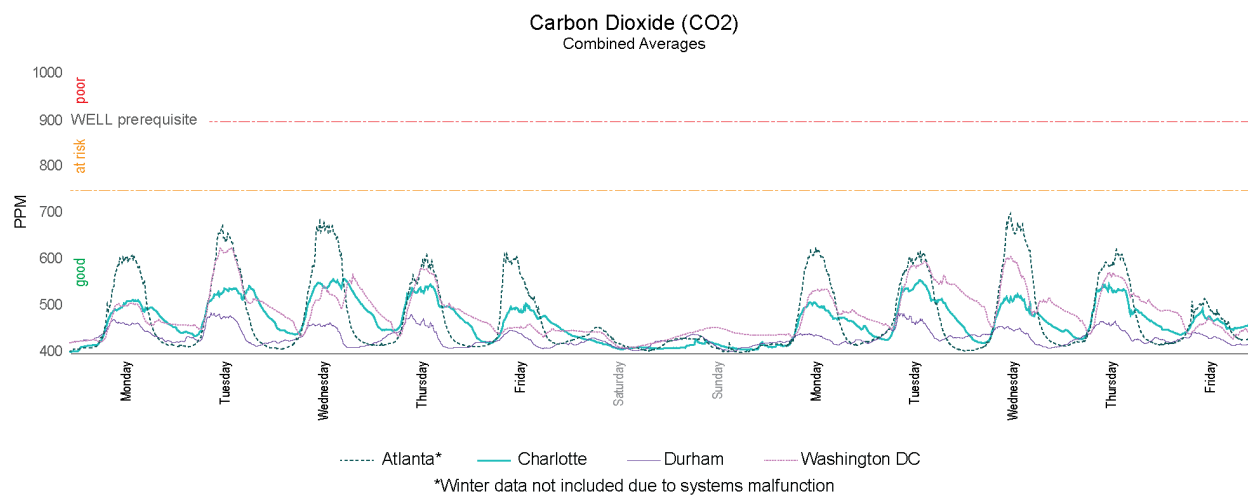


Figure 5, Average weekly CO₂ concentrations across four test offices

prerequisite threshold, registering 697 and 800 $\mu\text{g}/\text{m}^3$ respectively. However, they still fell within Kaiterra's 'good' air quality range, a qualitative evaluation informed by key building certifications such as WELL and RESET, which consider air quality to be 'good' when levels are below 1,005.5 $\mu\text{g}/\text{m}^3$ (Kaiterra). Washington DC and Atlanta were slightly higher with concentrations of 1,044 and 2,646 $\mu\text{g}/\text{m}^3$ respectively, both considered 'moderate' by Kaiterra's indoor air quality assessment. The Atlanta office, in particular, experienced notably high concentrations during the fall study, averaging 5,139 $\mu\text{g}/\text{m}^3$ during working hours due to ongoing construction activities. However, these levels dropped significantly to 1,997 and 802 $\mu\text{g}/\text{m}^3$ during the spring and summer study respectively, reflecting the impact of both material selection and effective ventilation. The rapid dissipation of these peaks suggests a high degree of outdoor air exchange and effective ventilation systems. It is worth noting that unlike CO_2 , tVOC concentrations varied dramatically throughout the day, week, and season, making them difficult

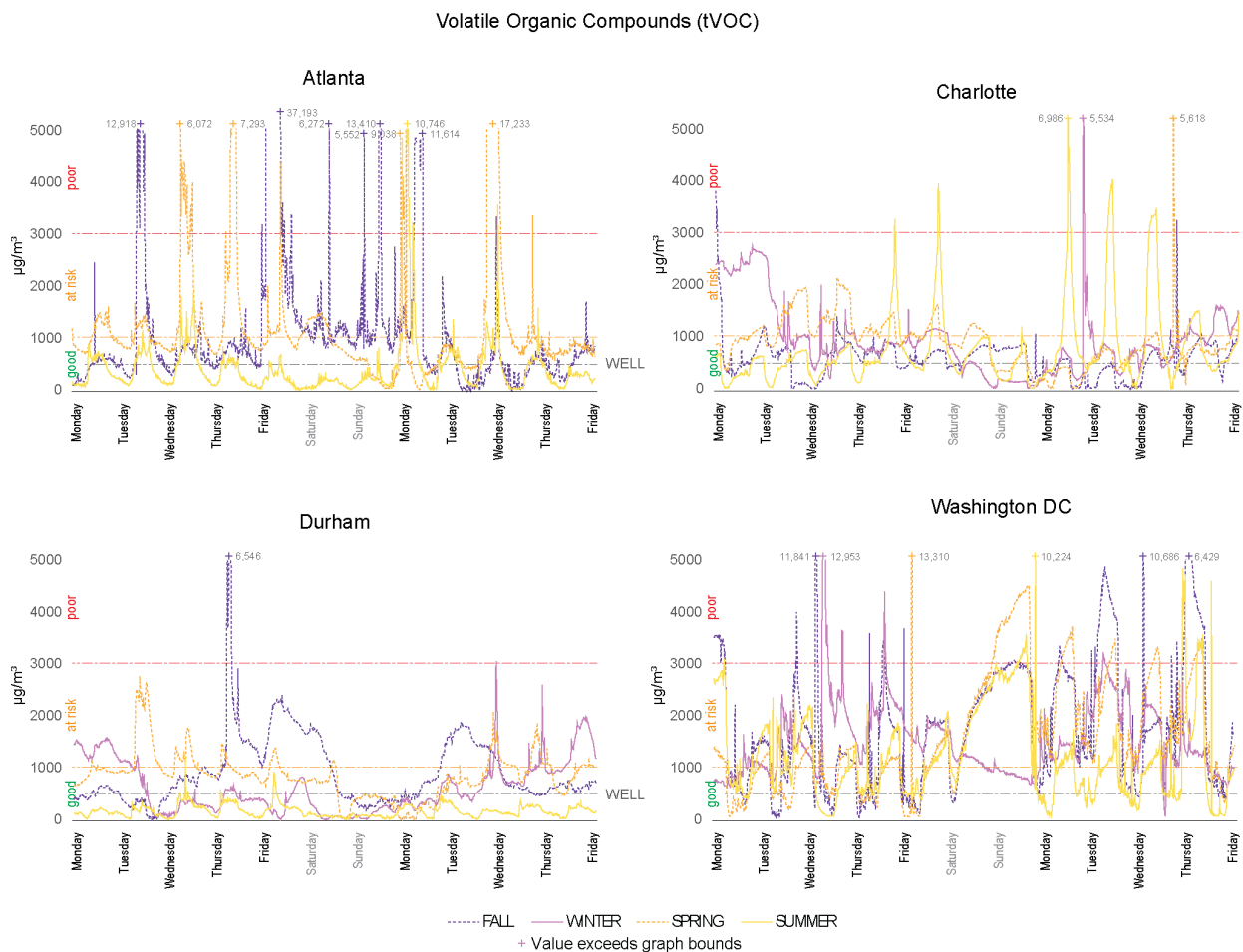


Figure 6, Average tVOC concentrations by season

to average. Therefore, figure 6 illustrates tVOC levels across all four study periods in each site, excluding the data from the Atlanta office's winter study.

Finally, the levels of particulate matter (PM_{2.5} & PM₁₀), which typically come from outdoor sources, were consistently low throughout the study. These results reflect minimal contributions from internal combustion sources and the implementation of high-quality filtration systems, which ensure that airborne particles, including dust and pollutants, are effectively captured and removed. Though still well below WELL thresholds of 15 µg/m³, the Durham office PM_{2.5} concentrations averaged at 5.3 µg/m³ for unknown reasons and would require further investigation. Atlanta followed closely with an average of 4.1 µg/m³, which is likely influenced by higher ambient particulate matter in the region, which is notably worse than in the other study locations. According to the American Lung Association's 2023 "State of the Air" report, Atlanta ranks 37th for the most polluted for year-round particle pollution and 100th for short-term particle pollution. Although some Washington DC occupants noted occasional smells of exhaust fumes when the front door was propped open, the maximum concentration of PM_{2.5} reached a maximum of 6.0 µg/m³. Notably, PM_{2.5} values in the Washington DC office were highest during non-working hours when ventilation rates were reduced, suggesting an interior source, though this typically peaked around 6-8 µg/m³ without exceeding 12 µg/m³.

While there are areas for improvement, the air quality findings reflect a strong commitment of the designers and facility managers to creating high quality indoor environments that support occupant's well-being and productivity. According to Kaiterra's overall index, all offices - except the Atlanta office – fell within the 'good' range'. The Atlanta office had a slightly higher index of 62, just above the 'good' threshold of 50, which Kaiterra categorizes as 'moderate'. This higher index is primarily attributed to elevated tVOC levels in the office. Overall, the air quality exceeds industry standards and while the offices may not fully align with the stringent WELL criteria, they performed well compared to other buildings in the United States.

Table 5: Average workday air quality data

| Location | CO ₂ (PPM) | tVOC (µg/m ³) | PM _{2.5} (µg/m ³) | Overall Index ³ |
|--------------------------|---|---|---|---|
| Atlanta ⁴ | 571 | 2,646 | 4.1 | 62 |
| Charlotte | 511 | 697 | .3 | 33 |
| Durham | 450 | 800 | 5.3 | 39 |
| Washington DC | 515 | 1,044 | .9 | 43 |
| Target Thresholds | < 900 ppm (Prereq.) ⁵ < 750 ppm (+2) ⁶ | < 500 µg/m ³ (Prereq.) ⁷ < 1,005.5 µg/m ³ 'good' ⁸ | < 15 µg/m ³ (Prereq.) ⁹ <12 µg/m ³ (+1) ¹⁰ <10 µg/m ³ (+2) ¹⁰ | < 50 'good' ⁸ 51 – 100 'moderate' > 100 'poor' |

B. Satisfaction with the environment

Survey respondents identified various sensory factors that influence their satisfaction with their workplace environment. Across all four sites, the open-office layout made acoustics an important consideration, with sound privacy and noise levels being among the top sources of dissatisfaction. Temperature and thermal comfort also emerged as key factors affecting productivity, with many respondents reporting discomfort in extreme conditions, whether too cold, warm, or humid, describing them as both unpleasant and distracting. In contrast, respondents were generally satisfied with the ease of interaction, views, and amount of light.

³ Kaiterra developed the overall index to provide a single snapshot of indoor air quality in a space while also identifying which pollutant to address first. By applying the same methodology and thresholds as the EPA's AQI standard, an index is calculated for each specific pollutant, with the highest value presented as the overall index.

⁴ Omitting winter data due to system malfunction 1/17/24 – 3/14/2024

⁵ WELL v2 A03 Ventilation Design, Option 4: Ventilation monitoring. 900 ppm or less, not more than 500 ppm above outdoor levels. Prerequisite.

⁶ WELL v2 A06 Enhanced ventilation design, Option 4: Ventilation monitoring. 750 ppm or less, not more than 350 ppm above outdoor levels. Max. 2 points.

⁷ WELL v2 A01 Air Quality, meet thresholds organic gases, option 2: TVOC continuous monitoring. Requires 500 µg/m³ or lower.

⁸ Kaiterra threshold (Kaiterra, n.d.)

⁹ WELL v2 A01 Air Quality, meet thresholds for particulate matter. Prerequisite for all spaces except commercial kitchen spaces and industrial in locations where the annual average PM_{2.5} level is below 35 µg/m³. As this study was being conducted, the EPA revised the primary annual PM_{2.5} standard by lowering the level from 12.0 µg/m³ to 9.0 µg/m³ based on emerging public health evidence, effective May 6, 2024 (Environmental Protection Agency 2024). Though indoor particulate matter is not currently regulated, organizations such as RESET and WELL are likely to also lower their allowed maximum levels for indoor PM_{2.5}.

¹⁰ WELL v2 A05 Enhanced Air Quality, Part 1: Meet enhanced thresholds for particulate matter. Max. 2 points.

While the full results are illustrated in the Supplementary materials (Figure 10), this section focus on overall satisfaction with the personal workplace, air quality, and the outdoor terraces.

Respondents were asked to rate their satisfaction with their overall personal workplace, as shown in Figure 7. The results reveal that 100% of respondents in the Charlotte and Durham reported that they were satisfied with their personal workplace environments. The Washington DC office showed a high satisfaction rate as well, though slightly lower at 95%, with one occupant claiming to be neither satisfied nor dissatisfied with their personal workplace. In the Atlanta office, 87% of respondents reported satisfaction. These satisfaction rates are notably higher than the CBE baseline condition, where only 68% of participants reported satisfaction with their personal workplace. Notably, the Charlotte, Durham, and Washington DC offices even exceeded the 94% satisfaction observed in in WELL certified buildings. Overall, these findings

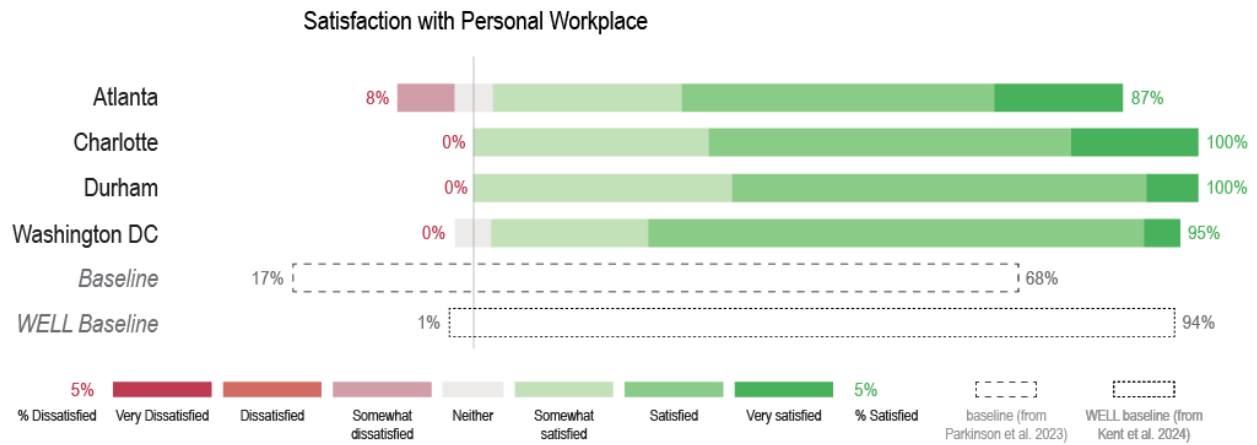


Figure 7, Satisfaction with personal workplace

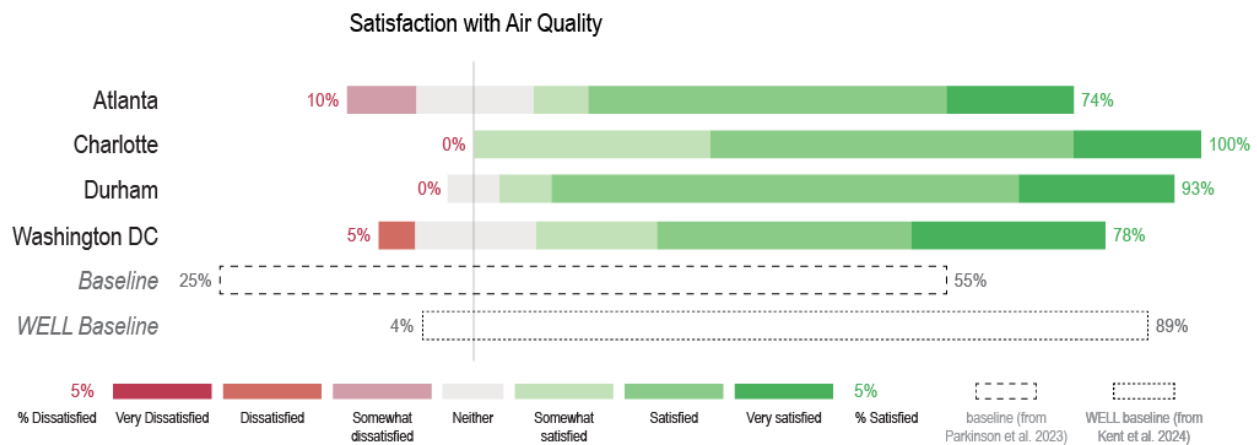


Figure 8, Satisfaction with air quality

suggest that employees in the study offices are generally very satisfied with their personal workplace environments.

When specifically asked about their satisfaction with air quality in the office, survey data reveals varying levels of satisfaction across the four office locations, illustrated in Figure 8. In the Charlotte office, 100% of respondents expressed satisfaction with the air quality, reflecting a highly positive perception. Durham followed closely with 93%. In contrast, the Washington DC and Atlanta offices reported lower satisfaction rates at 78% and 74%, respectively. Both of these offices also had a higher number of neutral responses. It is important to note that the lower satisfaction rates in the Atlanta office may be influenced by one of the surveys being conducted during the winter HVAC failure. During this period, satisfaction with air quality dropped to 64%, compared to 85% recorded during the summer survey. During the winter survey, occupants who expressed dissatisfaction cited concerns about a musty/stale odor, insufficient air movement, and a perceived lack of cleanliness in the air. This winter-related dip reflects a temporary issue, which could skew the overall satisfaction average. Despite challenges in the Atlanta office, the satisfaction with air quality in each of the four offices significantly exceed the CBE baseline, where only 55% of respondents indicated satisfaction with the air quality. Additionally, these figures are comparable to the satisfaction levels reported in WELL certified buildings.

All three offices with terraces, Atlanta, Charlotte, and Washington DC, reported overwhelming satisfaction with these spaces, as illustrated in Figure 9. Since terrace satisfaction was not covered in the standard CBE survey, baseline data for comparison is not available. Among those who were dissatisfied, common concerns included glare, insufficient shading, thermal discomfort, and technical challenges such as Wi-Fi and power accessibility. Respondents also articulated a desire for more character, greenery, and ambiance to further improve the terrace

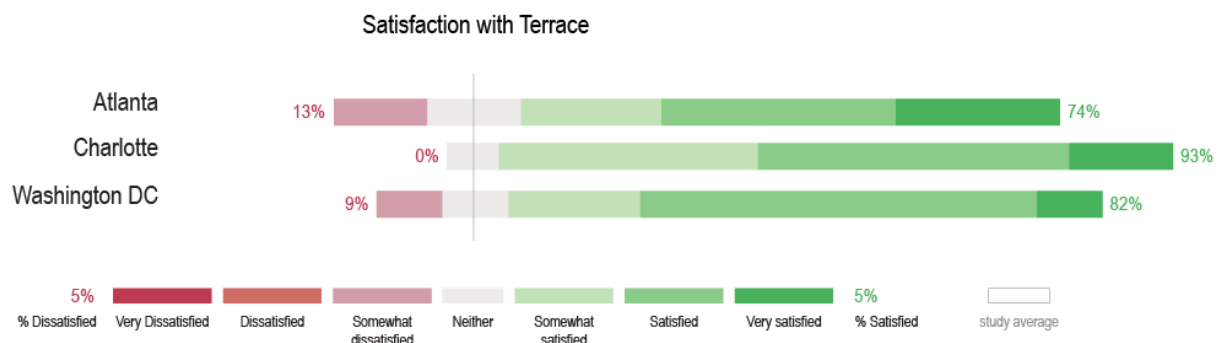


Figure 9, Satisfaction with terrace

experience. Feedback from the Charlotte office reflected the highest satisfaction rates, with 93%, followed by Washington DC and Atlanta with 82% and 74%, respectively. Despite expressing the lowest degree of satisfaction, participants from the Atlanta office demonstrated significantly higher engagement with the terrace with 39% of respondents indicating having used the terrace at least once a week in the past 30 days, compared with only 11% in Washington DC. In contrast, a notable 57% of respondents in the Charlotte office and 67% from Washington DC indicated that they did not use the terrace *at all* in the past 30 days. As anticipated, usage patterns varied significantly between winter and summer, reflecting the impact of temperature differences.

When asked about the most common reason for using the outdoor space, 58% of the total participants responded that they were seeking a change of scenery, 8% needed space, and 33% chose ‘other’ (break/lunch, access to fresh air/avoid the cold, social). No participants expressed dissatisfaction with the indoor environment, or a need for privacy as reasons for moving outdoors. When asked what type of activity they most commonly did in the outdoor space, none of the participants noted that they would conduct focused work, work-related virtual meetings/call, or personal calls. Instead, it was observed that the outdoor space was used entirely for social or recreational purposes.

Overall, the survey responses shed light on the multifaceted nature of occupant satisfaction with workplace environments, encompassing sensory factors, programmatic considerations, and the impact of specific workplace initiatives. Despite some challenges, such as acoustic issues and temperature extremes, employees generally reported high levels of satisfaction with their personal workplaces, air quality, and outdoor terraces. Notably, satisfaction levels in all four offices were substantially higher than the CBE baseline, and in many cases, exceeded the satisfaction observed in WELL certified buildings, particularly regarding air quality and personal workplace environments. The next step will be to explore the usage patterns of the outdoor terraces to further understand their role in workplace satisfaction.

C. Use of the Terrace

The behavioral analysis revealed several key insights into the use of the outdoor terraces. According to QR Survey responses, the primary reason for using the outdoor terraces was a ‘change of scenery’, with 70% of respondents citing this as their reason for stepping outside.

This suggests a strong desire among individuals to break away from their usual indoor environment, likely seeking a refreshing perspective or a mental reset. 23% of respondents mentioned ‘other’ reasons, such as “nice weather”, “fresh air”, or “mental health break”, which further underscores the terraces’ role in supporting personal well-being. Notably, only one respondent, from Washington DC, expressed dissatisfaction with the indoor environment as the reason for moving outside, specifically referencing concerns with lighting and furnishings.

Once on the terrace, the most common activities were casual, with 60% of respondents reporting they used the space to have a ‘meal or snack,’ followed by 35% ‘taking a break’. Only 5% of respondents claimed to engage in a ‘social activity’, however many responses were submitted around the same time, which may indicate a more communal experience. Importantly, none of the 40 respondents reported using the terrace for work-related tasks, reinforcing the terraces’ primary function as a space for relaxation rather than productivity.

Usage patterns varied by time of day and day of the week, with the highest activity on Fridays (30%) and significant usage on Mondays and Thursdays (23% each). The terraces were most frequently used between 12 and 2 PM, aligning with lunch breaks, with 50% of terrace visits occurring during this window. While there was a notable cluster of responses from the Atlanta office at 9:30 AM on a Friday morning, most terrace use occurred during or after lunch.

Terrace use occurred across a wide range of indoor air quality conditions, from a very good (index value of 14.5) to very poor (index value of 110). Notably, roughly half (55%) of outdoor visits occurred when the indoor air quality was worse than outdoor air, indicating minimal correlation between air quality and terrace use. Similarly, outdoor conditions during terrace use varied widely from 14.4 - 31°C (58 - 88°F) and 23 - 69% relative humidity, contrasting with the more stable indoor environment of 21.7 - 26.7°C (71 - 80°F) and 24 - 49% RH. The average outdoor condition during terrace use was 23.8°C (74.8°F) and 45% RH. Only two instances of outdoor use coincided with indoor CO₂ concentrations exceeding 1,000 ppm, both during the winter systems malfunction in the Atlanta office, when tVOC concentrations were also elevated beyond Kaiterra’s threshold for ‘poor’ quality indoor air. Despite these poor indoor conditions, respondents cited reasons such as “time for a break and it’s beautiful out!” and “nice weather”, rather than attributing their decision to air quality concerns.

In summary, the data suggests that the outdoor terraces primarily served as social and recreational spaces, rather than as extensions of the indoor work environment. The terraces were

used most frequently for meals, breaks, and occasional socializing, indicating their value in enhancing occupants' well-being and providing a mental reset during the workday. Contrary to the initial expectations, there was little evidence to suggest that poor indoor environmental conditions were a significant driver of terrace usage, with most respondents attributing their outdoor activity to personal or weather-related factors.

D. Qualitative feedback

Semi-structured interviews provided a valuable platform for a deeper exploration into occupants' perceptions of the indoor environment and the nuanced dynamics of their relationship with outdoor space in the workplace. While IAQ monitoring and occupant satisfaction surveys suggested a generally high level of contentment among the occupants, the interviews unearthed deeper sentiments indicating a latent dissatisfaction not fully captured by the quantitative metrics alone. For example, some respondents articulated feelings of being “trapped,” “confined,” or as if they were “stuck in a cold box.” Furthermore, data illustrates a noticeable contrast between participants' desire to spend more time outdoors during the workday and their actual behavior, often opting to enjoy outdoor activities during weekends or vacations instead of utilizing the available terrace spaces.

i. Dissatisfaction with “freshness” of air despite optimized ventilation

Given each building's adherence to rigorous air quality standards, one might expect occupants to be consistently satisfied with the respiratory experience in each office. However, satisfaction with air quality was also influenced by personal perceptions, environmental factors, and the overall sensory experience within a space. On a quantitative level, the air quality parameters met or exceeded industry standards, reflecting an optimally ventilated environment. However, when participants were asked to “describe your ideal workplace environment,” half communicated a desire for more “fresh air” in the workplace, despite the high quality of the provided indoor air. This indicates that these metrics did not fully capture participants' satisfaction, as they overlooked the sensory and emotional need for a deeper connection with nature in the workplace. This notion is revealed through key participant insights including,

I like real wind inside of the buildings. (A1)

I know we are in the middle of this city, could be a smoke or whatever, but to get the sensation that you're having fresh air, and not something that you're enclosed, even though [the indoor air] is good, but sometimes I don't think it is... (C4)

I would definitely love more fresh air, but it's kind of like, I'm not going to go pop open a window in the office. (DC1)

It would be nice to have fresh air. Although the air inside the office is probably better than outside, certainly in the summer, that's usually the case. (DC3)

Based on interview responses, the concept of “fresh air” extended far beyond the technical definitions used in green building standards, which often focus on pollutant levels and the quantity of filtered outdoor air supplied indoors. The users’ perceptions of fresh air also incorporated a spectrum of sensory experiences, including temporal changes, air circulation patterns, and natural sounds that significantly contribute to occupants’ perceptions of well-being within the workplace. Together, these elements contributed to a more holistic sense of well-being, creating an atmosphere that felt dynamic rather than static or artificial. The desire for such sensory diversity is apparent in the participants’ own words:

I can get this [view] through a window, but I can't get the feel of a seasonal change, and I can, which is part of the reason I go outside on a day like today when it's 70 degrees and it's supposed to be 85. (C3)

But it isn't even just the amount of lumens on the worksurface, it is how the light changes throughout the course of the day. You know I'm looking at the wall in our cafe right now, and one of the things I love is to see how the shadow made by the sun washing through the window frame and structure changes as the day progresses. You know, those are things that actually impact my happiness and comfort level quite a bit. (DC2)

When I'm at home, I can go touch the grass and the environment. I just feel that it's good. (A1).

These examples highlight a desire for a deeper connection with the more ephemeral qualities of the natural world, suggesting that while the indoor environment meets air quality standards and includes WELL features such as biophilia, access to views, and natural light, it may still lack certain elements essential for a truly pleasurable and memorable experience. These findings reveal a complex interplay between sensory experiences, nature, and established health metrics, exposing gaps in our understanding of what creates a fully satisfying environment. Such insights underscore the limitations of traditional air quality metrics, which often overlook the full

spectrum of what makes air feel truly “fresh” to individuals. The challenge, then, is to identify strategies that integrate these intangible qualities, crafting a workplace that not only adheres to air quality standards but also aligns with the sensory preferences and well-being of its occupants.

ii. Preference for outdoor spaces despite limited terrace use

Despite spending the bulk of the work week indoors, an overwhelming majority of participants (88%) articulated a significant increase in outdoor time during non-working hours, particularly on weekends and during vacations. One Atlanta office participant highlighted a substantial contrast, stating, “Vacations I would say 70% of my time [I’m outdoors], but during my week working I would say 10% or less” (A1). This stark contrast underscores a deliberate choice among participants to prioritize outdoor activities when not engaged in professional responsibilities. Whether it is seeking relaxation, physical activity, or simply a change of scenery, the preference for outdoor experiences during leisure time highlights a deep-seated human need to connect with the natural world.

When participants were asked, “Which condition do you believe to be healthier for you, inside or outside?” a notable consensus emerged, with 10 out of 14 participants expressing the view that the outdoor environment is generally perceived as healthier. Three participants expressed that a mix or balance of indoor and outdoor exposure was best while one Charlotte office participant expressed that inside was healthiest for them, citing allergy control. As the exact metrics used to define “health” were purposefully not stated in the question, individual definitions appeared to vary among participants. Mental health considerations emerged as a significant factor in shaping their responses. Many described their time outdoors as refreshing, invigorating, and essential for maintaining a positive mindset. Without access to outdoors, for instance, one Washington DC office respondent noted that they would “go crazy if I can’t go outside” (DC3), emphasizing the psychological impact of limited access to nature, and supporting research that the outdoors serve as a vital outlet for stress relief and mental rejuvenation (Park et al. 2010; Ulrich et al. 1991; Kaplan 1992; Bratman et al. 2019). This strong preference for the outdoor environment, both for its perceived physical and mental health benefits, underscores the importance of integrating nature into the workplace and highlights the essential role that outdoor spaces play in promoting overall well-being.

Referring specifically to the workplace terraces provided in the office, several participants emphasized the role of these outdoor spaces as critical spaces for a mental break. One Atlanta participant, for example, expressed that “it’s important as a decompression space for lunch or just a change of venue... So that’s primarily what I use the space, the outdoor deck for, is for reset, when I need to force my brain to move on to other subject matter” (A2). Others viewed the space as an opportunity to retreat or escape from the office environment. Some other comments include:

I use it to get away if I'm having a particularly stressful day. (DC2)

I like when we go out for lunch and take a walk. That's a nice break. More for the mental break than anything. It's nice to just step away and let your eyes relax from your computer screen. (C6)

And I think that's really important to have a space where it kind of feels as if you can take a break because you can't always just go to the cafe. So, it doesn't still feel like you're in the office. I think it's really nice and important that we have a space like that where if you need 30 minutes, you can exit the office and feel like you're not in a work environment. (DC1)

Ultimately, while participants recognized the idealized concept of outdoor workspaces, they questioned the practicality of consistently using them during the day, again citing concerns of glare, thermal comfort, and technological limitations. Despite these concerns, each of the participants mentioned that they enjoyed having it available as an “amenity” or a “perk”. This sentiment was articulated by one Charlotte office respondent, saying, “It's one of those things, having the access to the outside, even though I don't use it as much as other people, it's nice to know it's there. I kind of think of it as when I lived in New York, I didn't go to Broadway a whole lot, but it was nice to know that I had the option” (C5). While the outdoor spaces are not extensively utilized for work-related tasks, they play a valuable role in the workplace environment. However, the discrepancy between the perceived benefits and the actual usage patterns underscores the need for tailored strategies to overcome barriers and encourage regular utilization.

The participants’ interview insights shed light on the complexities of integrating outdoor spaces into the work routine and the need for thoughtful interventions that reconcile sensory perceptions of indoor comfort and the practical demands of human health and well-being. While outdoor spaces hold value in the work environment, the spaces examined in this study did not

fully satisfy participants' desire for greater access to fresh air and nature in the workplace. In response, a more integrated approach to urban architecture and workplace design is necessary – one that extends beyond physical layout to infuse natural elements and fresh air into the indoor environment, ultimately fostering a more holistic and satisfying workplace experience.

Discussion & Conclusions

Nature is characterized by dynamic spatial gradients and temporal shifts in light, sound, temperature, humidity, wind, and radiation, driven by seasonal fluctuations and intermittent events. Research demonstrates that the human body inherently craves this type of diversity, and the broad range of thermal conditions found in outdoor spaces contributes significantly to increased thermal satisfaction indoors (Parkinson 2016; Spagnolo and de Dear 2003). Despite this inherent preference, contemporary conditioning technologies often prioritize consistency and uniformity, resulting in environments that are intentionally shielded from environmental stimuli and isolated from the unpredictable factors of weather, climate, and human activity (Barber 2020). Despite the high standards of the workspaces in this study, which include well-filtered outdoor air, ample natural light, indoor greenery, and dedicated outdoor terraces, there is a notable disconnect between the physical environment's perceived quality and the psychological and emotional needs of the occupants. Although these environments excel according to industry standards, participants still expressed dissatisfaction with their indoor experiences, reflecting a deeper, unfulfilled need for a connection to nature during the workday. This discrepancy highlights the importance of addressing not only the physical but also the psychological and emotional aspects of the workplace environment.

This study explores the nuanced relationships between outdoor access and workplace satisfaction, acknowledging the positive perceptions associated with the outdoors while also revealing challenges and constraints that limit the practical utilization of outdoor space for office work. The findings offer valuable insights into the environmental preferences and experiences of building occupants across the four buildings studied, three of which feature outdoor terraces. Despite limited technical knowledge of air quality and health metrics, participants exhibited a clear preference for outdoor spaces, citing the perceived health benefits, particularly for mental well-being. Additionally, participants were overwhelmingly interested in the possibility of having

increased fresh air in the workplace despite the high-quality ventilation air that exists. The desire for experiential conditions beyond the quantifiable metrics, such as “real wind” and seasonal change, suggests a need to align indoor environments more closely with occupants’ sensory preferences and the dynamic qualities of outdoor environments.

Despite the participants’ positive perceptions of the outdoor terraces and their association with healthful environments, the data reveals a significant gap between the expressed desire for outdoor access and the actual utilization of these spaces, particularly for work-related activities. While participants expressed overwhelmingly positive feelings toward these spaces in both the interviews and surveys, the outdoor spaces predominately served a recreational function, used for team happy hours, lunch breaks, and informal gatherings. Participants listed numerous hindrances contributing to the limited use of the outdoor spaces for work, including glare, urban noise disruptions, and the need for desk amenities like Wi-Fi and multiple monitors. These practical barriers restrict the effective use of outdoor spaces for work, reinforcing the preference for the convenience of indoor work environments.

The stationary nature of work routines further compounds the reluctance to shift work to outdoor spaces. This pattern of use contrasts with the more flexible approach some participants adopt when working from home, where they frequently change locations throughout the day. One particular respondent who said they did not use the outdoor space at the office because they needed the desk amenities also said they work on their laptop at home and tend to shift locations fairly regularly throughout the day. As workplaces continue to evolve, acknowledging and accommodating these shifting preferences becomes necessary for creating work environments that align with the diverse needs and expectations of today’s workforce. While the outdoor terraces provide employees with a valuable opportunity for respite, they fall short of breaking the uniformity of the indoor environment and fail to create a truly integrated and dynamic workplace experience. This discrepancy highlights the importance of addressing not only the physical but also the psychological and emotional aspects of the workplace environment.

These findings suggest that creating an environment that resonates with innate human physiology extends beyond optimizing physical conditions alone. The desire for a more integrated experience that harmonizes indoor and outdoor elements calls for a departure from conventional workplace design strategies. In response, designers should consider adopting a transformative approach that embraces unconventional modes of thinking to accommodate the

dynamic needs and expectations of today's workforce. Pursuing an optimal workplace experience demands a departure from the ordinary, compelling designers to embrace unconventional modes of thinking to forge a transformative path toward a 'blurred' architecture that seamlessly integrates inside and out. Providing urban workplace strategies that addresses sensory elements and actively promote occupant health, satisfaction, and well-being, requires a disruptive approach that defies the workplace status quo and embraces unconventional modes of thinking.

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AI Statement

Generative artificial intelligence tools, including Grammarly and ChatGPT, were used in this paper to improve grammar and clarity of the writing and provide technical support for data analysis tools like MS Excel and Python. All data, figures, content, and conclusions are solely those of the author.

Statement of Co-Authorship

As lead author, Elizabeth L. McCormick was responsible for designing and conducting the study, as well as drafting the manuscript, including the literature review, data analysis, and the development of the discussion and conclusion sections. As a co-authors, Dr. Traci R. Rider and Dr. Jianxin Hu provided guidance on research design and concept, offering ongoing support throughout the writing process. Both Dr. Rider and Dr. Hu reviewed and edited the manuscript.

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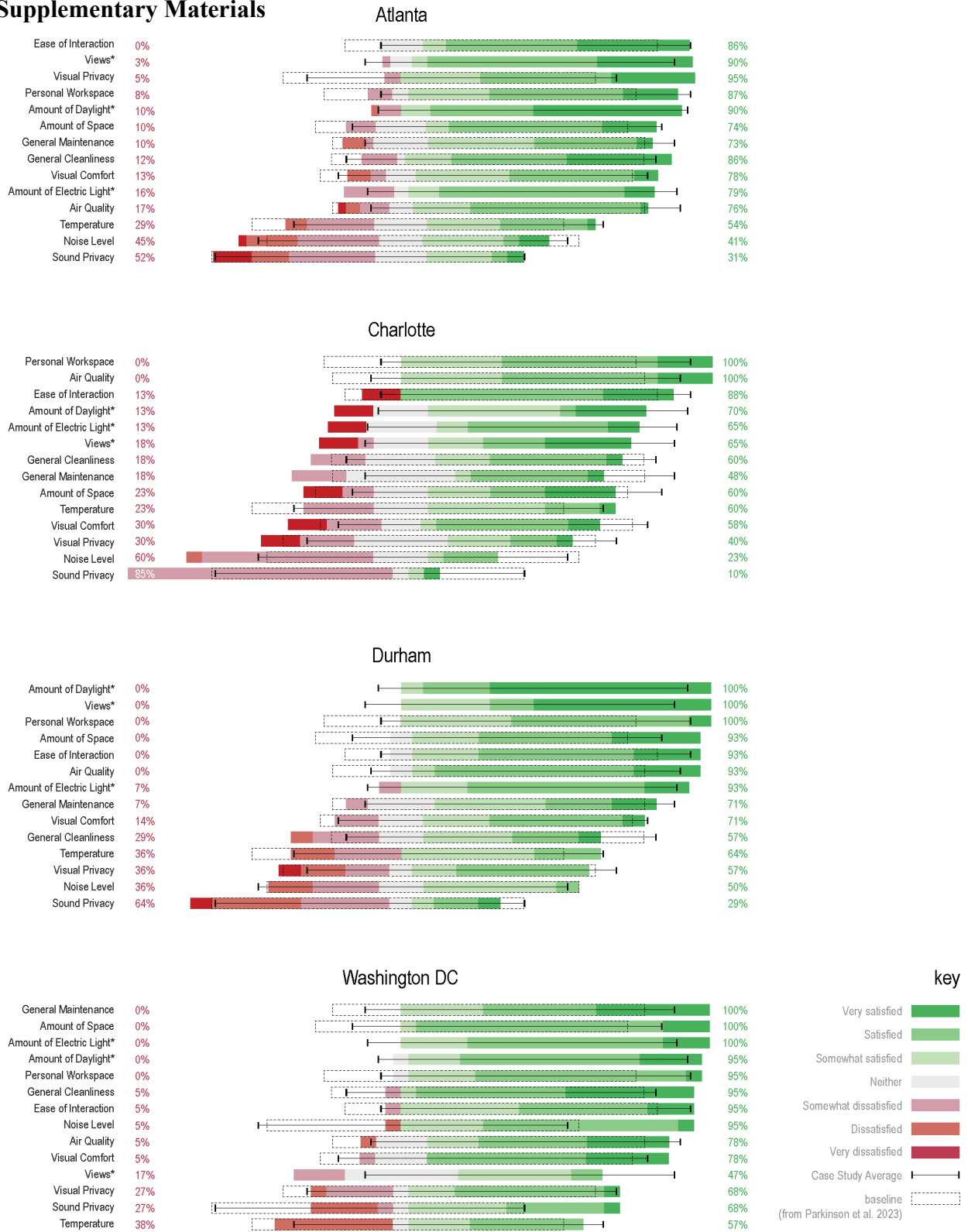
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Supplementary Materials



Organized from lowest to highest dissatisfaction

*the original (2002) version of the survey did not include specific questions on electric lighting, daylight, and views so baseline data does not exist for these categories.

Figure 10, Occupant Satisfaction Survey (Full Results)

CHAPTER 3: ARTICLE TWO

Inside Out:

Perceptions and Realities of Ambient Pollution and Indoor Air Quality in Four Office Buildings in the United States Southeast.

Abstract: Despite increasing awareness of the health risks associated with long-term exposure to poor quality indoor air, many Americans often perceive outdoor air pollution as a more significant threat. This perception is rooted in early 20th-century fears and values that persist today; even as modern construction practices have altered the nature of these risks. Although indoor air quality has only recently gained significant attention, it is a critical determinant of occupant satisfaction and well-being, with profound implications for human health, productivity, and performance.

This paper examines the intricate relationship between measured environmental conditions and psychological perceptions by analyzing both indoor and outdoor air quality data alongside qualitative feedback from four urban office buildings located in the US Southeast (Atlanta, Charlotte, Durham, and Washington DC). The study revealed that, contrary to common beliefs, indoor air is not uniformly superior to outdoor air, even though the four spaces in the study performed significantly better than similar buildings across the United States. These results reveal that indoor air is not consistently cleaner or healthier, emphasizing the complexity of workplace air quality dynamics in the United States. By bridging historical perceptions with contemporary psychological contexts, this research advocates for a more holistic approach to improving occupant health and satisfaction in urban office environments.

Introduction

From a historical perspective, attitudes toward outdoor air have a complex history shaped by fears of respiratory diseases and coal-driven pollution, both considered blights of urban living. Throughout the late 19th and early 20th centuries, urban centers were often synonymous with poor air quality, as industrial activities and widespread use of coal fueled significant environmental and health concerns. Smog-filled skies and soot-covered streets became symbolic representations of urban pollution, fostering widespread anxiety about the air people breathed. The threat of respiratory diseases, such as tuberculosis and pneumonia, further compounded these fears, embedding a deep-seated fear of outdoor air among urban populations.

The evolution of the built environment, driven by advancements in mechanical conditioning technologies, catalyzed a paradigm shift in how air was perceived. This shift in perception not only altered the way air was viewed but also significantly influenced the expectations and standards for indoor environments. This transformation in awareness redefined air “from menace to modernizing agent, that is, from being generally perceived as a given carrier of foul smells, germs, and disease to its promotion as a machined catharsis made available to all through modern technology” (Böer 2019, 49). The advent of air conditioning, prioritizing comfort, efficiency, and control over natural elements, laid the foundation for the present cultural age, often referred to as the air-conditioning era (McCormick 2024). Air conditioning emerged not just as a means of comfort but as a symbol of modernity and progress, reconfiguring the relationship between humans and the environment (Cooper 2002; Ackermann 2002). This period has significantly shaped social and behavioral patterns, influencing how we perceive and interact with health, nature, and the built environment.

The shift towards viewing mechanically conditioned indoor environments as safe and healthy, in contrast to the growing concerns about the toxicity and unpredictability of outdoor air, was clearly reflected in cultural representations. For example, on the cover of the June 1929 issue of *The Aerologist*, the first trade journal on air conditioning, a woman and her child find refuge within a windowless, artificially lit domestic space enhanced by modern technology and shielded from the hazardous outdoors. The illustration portrays the home as a sanctuary of safety and purity, contrasting sharply with the outside world, where a man in business attire is shown wearing a gas mask, protected from the perceived dangers lurking outdoors. The portrayal of the indoor spaces as sanctuaries was a significant cultural development, influencing everything from



Figure 1, Magazine Cover, 1929

architectural design to public health policies (Campbell 2005; Tomes 1998). Consequentially, this shift impacted how spaces were constructed, the standards for air quality, and the broader public perception of health and safety within urban environments. As air conditioning became more widespread, the dichotomy between indoor and outdoor air quality became more pronounced. The cultural impact of this shift was profound.

The imagery from *The Aerologist* is a powerful visual testament to these historical attitudes where technological innovation was directly linked to perceptions of health and quality of life, reflecting broader societal trends towards modernity and industrialization. This historical context is necessary in understanding contemporary attitudes towards indoor and outdoor air quality, as many of the underlying fears and values from the early 20th century continue to shape perceptions today. Despite the growing awareness of the risks associated with long-term exposure to unhealthy indoor air, many Americans still perceive outdoor air pollution as a more significant threat than indoor air. A *ConsumerStyles* survey found that 47.9% of American adults were concerned about outdoor air quality, while only 17.3% reported concerns about indoor air quality (Shin et al. 2019). Additionally, a survey of parents with children experiencing health issues revealed that fewer than 1% of these parents were aware of the risks associated with indoor environments (Dziubanek et al. 2013). By investigating these evolving perceptions and comparing them with empirical air quality data, this study seeks to bridge the gap between historical influences and current understandings, ultimately providing insights into how our

awareness and management of indoor and outdoor air quality can be improved in the context of the modern workplace.

Dangers posed by long-term exposure to unhealthy indoor air have become more apparent in recent years, as building materials, furnishings, cleaning products, and even occupants' activities contribute to the indoor air composition. In fact, there are occasions where outdoor air conditions are cleaner than indoor air, based on available measured contaminants (González-Martín et al. 2021; Shrestha et al. 2019; Myers and Maynard 2010). This disparity challenges the conventional assumption regarding indoor sanctuaries and prompts a deeper examination of the factors influencing air quality within different environments. In response, this study explores perceptions of indoor and outdoor air quality in and around urban office buildings in the US Southeast, comparing qualitative assessments of health perceptions with measured air quality data. By examining how contemporary attitudes towards indoor and outdoor air quality have evolved, this paper aims to provide a nuanced understanding of the factors that shape these perceptions. This work also seeks to highlight the ongoing relevance of historical anxieties and technological advancements in influencing how we conceptualize and engage with the built environment.

Background

Indoor air quality (IAQ) is a major determinant of indoor satisfaction; however, its study has only gained significant attention in recent years. It is important to recognize the implications on occupant well-being and productivity, bridging the gap between the physical environment and human performance. As emerging evidence increasingly links indoor air pollution to a range of health problems, understanding the current state of indoor air quality issues is essential in addressing these risks effectively. This section explores the metrics used to determine both ambient and indoor air quality as well as how buildings are traditionally ventilated.

A. Ambient (Outdoor) Air Quality

Ambient data is gathered from local weather stations, monitored by the United States Environmental Protection Agency (EPA) using the air quality index (AQI), which is calculated based on the five major air pollutants regulated by the United States' Clean Air Act. These five pollutants have been identified to have the strongest evidence for public health concern,

including ground-level ozone (O₃), particle pollution (particulate matter, PM_{2.5} and PM₁₀), carbon monoxide (CO), sulfur dioxide (SO₂) and nitrogen dioxide (NO₂). The AQI metric provides a simple way to understand how clean the air is and the associated health risks. AQI typically ranges from 0-500, with lower values indicating better air quality (US EPA 2018).

O₃ is a major component of smog from vehicles and other industrial functions. Because it forms photochemical reactions with other pollutants, the highest levels of ozone are experienced in sunny conditions, which is why it is higher in the daytime and during summer months. CO is produced by the incomplete combustion of carbonaceous fuels; in cities, it is most commonly produced by motor vehicles. NO₂ is also a product of combustion of fuels and is closely linked with asthma and other respiratory conditions. SO₂, a product of the combustion of sulfur-containing fossil fuels and is a major pollutant in many parts of the world, particularly where coal is used as the primary source of electricity. However, as of 2021, SO₂ is no longer included in EPA reports as SO₂ concentrations can be quite localized and may not accurately reflect broader geographical conditions (US EPA 2024). Particulate matter refers to inhalable particles that come from a combination of indoor and outdoor sources. Larger particles, such as PM₁₀ come from pollen, sea spray, wind-blown dust from erosion, agricultural spaces, roadways, and mining, while the finer particles, such as PM_{2.5} come from combustion of fossil fuels, industry, wildfires, and vehicles. PM_{2.5} is the most widely used indicator for assessing the health effects of air pollution exposure across the globe (World Health Organization). For most urban areas in the

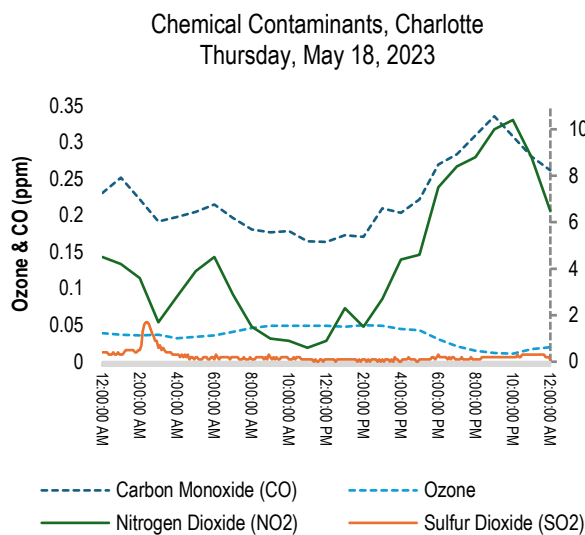


Figure 2, Chemical Contaminants in a 24-hour period
Data from EPA Air Quality System (AQS)

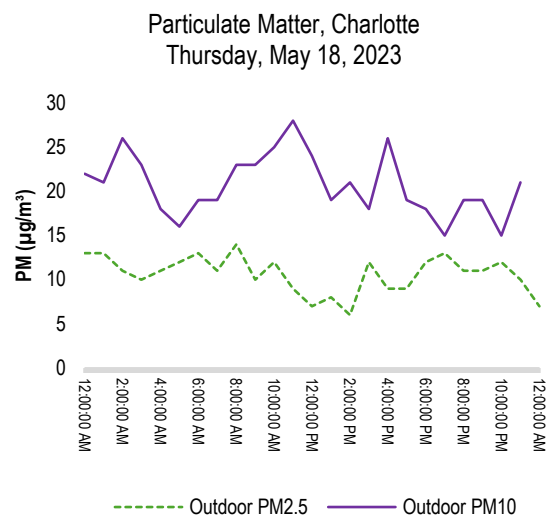


Figure 3, Particulate Matter in a 24-hour period
Data from EPA Air Quality System (AQS)

United States, ground-level ozone is the highest pollutant in the summer and particulate matter is the highest for the remainder of the year. Concentrations of these pollutants fluctuate throughout the day, as shown in Figures 2 and 3.

B. Indoor Air Quality

While ambient air pollution has significantly decreased in the United States since the introduction of the Clean Air Act in 1970, the quality of indoor air poses an entirely unique and often understated threat. According to the US EPA (1987), indoor air can actually be two to five times worse than outdoor environments, largely due to the use of synthetic materials in buildings, which can emit contaminants. Some of these contaminants can have long-term health effects that may not become apparent for many years (González-Martín et al. 2021). Additionally, about 65% of exposure to outdoor air pollution actually occurs indoors (Fisk 2015; Ben-David and Waring 2016).

Soon after the superinsulation and energy efficiency movement of the 1970s, the World Health Organization (WHO) identified health issues related to indoor air as Sick Building Syndrome (SBS) in 1983. SBS encompasses a range of physical, chemical, and psychological factors affecting human health and comfort, including asthma, allergies, watery eyes, cough, headache, and fatigue. More severe conditions can include cardiovascular issues, cancers, and reproductive problems (Kraus 2016; Joshi 2008). Research indicates that upper respiratory symptoms and fatigue are more common in sealed buildings with mechanical systems compared to those with natural ventilation (Rios et al. 2009). Moreover, global allergy rates are rising, particularly in the developed world attributed to chemical exposure in low-quality indoor air (Kim et al. 2013). Evidence suggests that the substantial increase in measurable human impacts is linked to environmental exposures rather than genetic changes (Sundell 2004). A recent study published by BMJ, a leading medical journal, reveals that exposure to air pollution, particularly particulate matter, is associated with a heightened risk of clinical dementia and cognitive decline (George 2023), even when exposed to concentrations below current EPA standards.

The pollutants most studied indoors include ozone, carbon monoxide, particulate matter (PM_{2.5} and PM₁₀), described above, as well as volatile organic compounds and formaldehyde. Though carbon dioxide (CO₂) is not considered a particularly toxic air contaminant, nor is it regulated by the EPA in ambient conditions, it can serve as a useful gauge of ventilation

efficiency inside buildings, indicating how much fresh air is getting into a space. Without proper ventilation, other indoor air pollutants can accumulate and impact occupant health and productivity (Allen et al. 2016). Monitoring CO₂ levels can help identify areas that require increased ventilation and air exchange. Because indoor concentrations largely come from human respiration (breathing), they can also provide useful insights into occupancy patterns. CO₂ levels in the atmosphere tend to remain relatively stable throughout the day, but there can be slight seasonal variations throughout the year. The National Oceanic and Atmospheric Administration (NOAA) reported that atmospheric CO₂ levels averaged 419 parts per million (ppm) in October 2023 and 425 ppm for the month of March 2024, as measured at Mauna Loa Observatory in Hawaii (NOAA 2024). Ambient CO₂ measurements provide a reference point for the minimum expected CO₂ level inside a building. In addition to being an indicator of ventilation efficiency, high indoor CO₂ levels can lead to occupant discomfort and reduced cognitive function (Allen et al. 2016).

In workplace settings where there is limited combustion activity (i.e. cooking, fireplaces, smoking, or burning candles), indoor particulate matter typically comes from outdoor sources. Though this study monitors both PM_{2.5} and PM₁₀, observations revealed nearly identical readings for both, suggesting that the filtration systems in the building effectively removed the vast majority of particles greater than 2.5 microns in aerodynamic diameter. As this study was being conducted, the EPA revised the primary annual PM_{2.5} standard by lowering the level from 12.0 µg/m³ to 9.0 µg/m³ based on emerging public health evidence, effective May 6, 2024 (Environmental Protection Agency 2024). Though indoor particulate matter is not currently regulated, compulsory frameworks, such as the WELL Building Standard (IWBI) and RESET (Regenerative Ecological Social Economic Targets), are likely to also lower their allowed maximum levels for indoor PM_{2.5}.

Volatile organic compounds (VOCs) originate from a variety of sources commonly found in indoor environments, including cleaning supplies, paint, adhesives, furniture, carpets, and building materials that can release VOCs over time. Additionally, electronic devices, personal care products, and even reheating food in the microwave can contribute to the emission of VOCs. Exposure to high levels of VOCs can have adverse effects on health, including headaches, dizziness, eye, nose, and throat irritation, as well as respiratory issues (Kim et al. 2013; Jones 1999). As the name suggests, total volatile organic compounds (tVOC's) include a

large number of complex compounds, and the commercial-grade sensor chosen for this study measures a mixture 22 VOC's¹ as defined by Mølhave et al. (1997). Prolonged exposure can exacerbate chronic health conditions or even lead to more serious health problems.

As observed during the COVID-19 pandemic, fresh air can also significantly impact the spread of disease indoors. Despite significant advances in modern medicine, infectious diseases such as bronchitis and pneumonia remain a risk in high-density environments, such as healthcare facilities where susceptible individuals congregate in close quarters controlled by mechanical ventilation. Healthcare-associated infections (HAI) can affect 5-15% of hospitalized patients and 9-37% of intensive care unit (ICU) patients, with significantly higher percentages in resource-limited conditions (National Center for Biotechnology Information and U. S. National Library of Medicine 2009). Escombe et al. (2007), studied eight hospitals in Lima, Peru to explore the difference between natural and mechanical ventilation and the effects of the two on the institutional transmission of airborne infection. This study included five hospitals built pre-1950 and three 'modern' hospitals built between 1970 and 1990. They studied 70 naturally ventilated clinical rooms against 12 mechanically ventilated negative-pressure respiratory isolation rooms within these facilities. Results showed that the risk of airborne contagion was significantly lower in the older, naturally ventilated facilities (11%), particularly those with high ceilings and large windows on more than one wall. On the other hand, the modern buildings under study had a significantly higher risk of infection (33%), particularly in the mechanically ventilated rooms with sealed windows, even while meeting or exceeding local ventilation guidelines. Additionally, the study found that the natural ventilation from open windows was more effective than mechanical ventilation against tuberculosis infection, even on days with little wind (Escombe et al. 2007).

C. Ventilation in Buildings

Until the 20th century, ventilation was primarily driven by comfort rather than health, due to limited understanding of indoor air quality issues outside of industrial settings. Before the 1930s, ventilation standards largely aimed to control smells, as body odors from humans were

¹ Compounds measured include: *n*-Hexane, *n*-Nonane, *n*-Decane, *n*-Undecane, 1-Octane, 1-Decene, Cyclohexane, *m*-Xylene, Ethylbenzene, 1,2,4-Trimethylbenzene, *n*-Propylbenzene, *a*-Pinene, *n*-Pentanal, *n*-Hexanal, Iso-propanol, *n*-Butanol, 2-Butanone, 3-Methyl-3-butanone, 4-Methyl-2-pentanone, *n*-Butylacetate, Ethoxyethylacetate, 1, 2-Dichloroethane.

perceived as the main source of indoor pollution (Sundell 2004; Yaglou et al. 1936). It wasn't until the late 1960s, when research emerged on radon and formaldehyde concentrations in homes, that the health effects of indoor air quality began to gain attention (Sundell 2004). Following this period, the oil crisis of the 1970s heightened environmental concerns around the use of fossil fuels for heating and cooling, particularly from foreign sources, leading to a new focus energy efficiency and improved construction standards. Buildings were initially designed to 'breathe' naturally, though this was often uncontrolled due to poor construction and the variability of outdoor conditions. As buildings were made to be more airtight to improve energy performance, the reduced fresh air exchange often resulted in indoor air quality issues affecting health and comfort.

ASHRAE Standard 62, which governs ventilation rates to ensure acceptable indoor air quality, is the primary standard in the United States for regulating ventilation rates in buildings. Initially published in 1932 to safeguard "occupants' health, safety and well-being" (ASHRAE 1973), Standard 62 was not considered regulatory until it was incorporated into buildings codes beginning in 1989 (Persily 2015). Despite their early focus on occupant comfort, ASHRAE members did not formally vote to integrate health considerations into their standards until 1999. At that time, the board of directors included a disclaimer noting that compliance with these standards "shall not make any claim or guarantees that compliance will provide health, comfort or occupant acceptability, but shall strive for those objectives" (Persily 2015). The evolution in ASHRAE's standards reflects a broader shift from an initial emphasis on comfort to a more comprehensive approach that increasingly incorporates health considerations, setting the stage for the development of more specialized guidelines in response to emerging challenges.

In response to the COVID-19 pandemic, ASHRAE introduced its first health-based ventilation standard, Standard 241P, Control of Infectious Aerosols, in May 2023. This standard outlines requirements for ventilation, filtration, and air-cleaning systems to reduce airborne virus exposure. During the pandemic, increasing outdoor air supply to 100% to mitigate virus transmission (Fadaei 2021), a strategy that was endorsed by major international heating, ventilation, and air-conditioning (HVAC) organizations including ASHRAE (US), REHVA (Europe), and SHASE (Japan). While all of these guidelines stressed the importance of fresh air; specific ventilation rates for eliminating airborne particles were not clearly defined (Guo et al. 2021). The consensus among these agencies was that while the total elimination of indoor COVID-19 transmission is unattainable, even with strict controls of the HVAC system and

robust filtration systems, infection risk can be significantly reduced through comprehensive measures and ‘bundle control strategies,’ including increased ventilation, social distancing, and personal hygiene (McCormick 2024).

Methods

While human indoor comfort can be informed by a physical, biological response, there are also contextual elements and social constructs that influence an individual’s response to quantifiable metrics. Given the intricate relationships between people, systems, and the built environment, which are influenced by the complex interplay of social, economic, cultural, environmental, technological, and behavioral factors, mixed-mode research methods are best-suited to explore these intricate interactions within the field of architecture (Aksamija 2021). Mixed methods grounded theory (MM-GT), a term coined by Johnson et al. (2010), is used to produce explanatory relationships in contextual settings. Because this research operates between qualitative and quantitative data sets, it was important to identify and dynamically blend the conflicting demands of the *ideographic* knowledge (contextual) produced by qualitative research and the *nomological* knowledge (universal) produced by quantitative research (Ibid). In response, this study compares the physical metrics of environmental space, through both indoor and outdoor air quality monitoring, in tandem with the human behavioral response with data from qualitative interviews of four office buildings in the US Southeast to detect and identify emergent themes.

This study spanned eleven months, with continuous indoor air quality monitoring conducted across four unique office spaces throughout the year. Focused study periods were scheduled once per season, each lasting two weeks. Semi-structured interviews were held with building occupants in the fall and spring. The study’s procedures were approved by the North Carolina State University (NCSU) Institutional Review Board (IRB #25686). A detailed description of these methodologies and comprehensive insights into the examined buildings will be provided in the following sections.

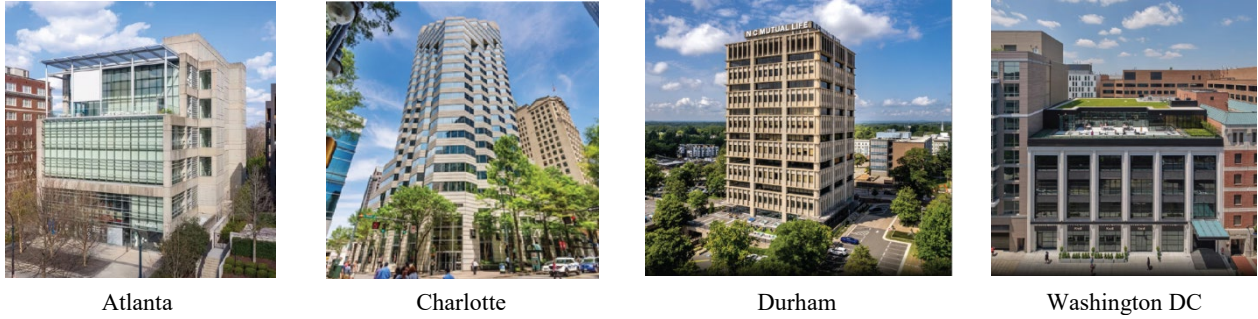


Figure 4, Study Buildings

A. Study Buildings

This research examines commercial office buildings in major metropolitan areas in the Southeast United States, including Atlanta, Charlotte, Durham, and Washington DC. The region’s climate is humid and subtropical, with moderate winters and hot, humid summers. The study sites fall within ASHRAE climate zones of 3A (Atlanta and Charlotte) and 4A (Durham and Washington DC). All the offices belong to the same international architectural design firm, which employs over 2,500 people globally and is recognized for its expertise in sustainable design. While the Charlotte and Durham offices operate together as a single North Carolina practice, the other offices function independently.

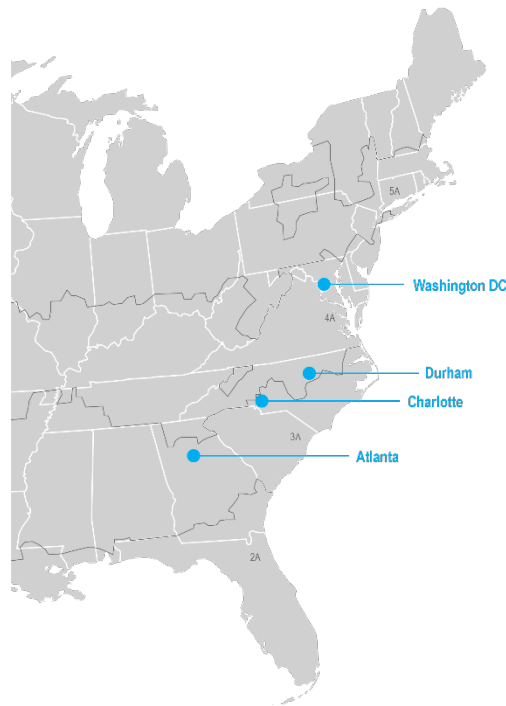


Figure 5, Study Locations

The offices were selected for the study due to their location in a similar climate, however each office differs in size and occupancy, offering a range of environments for studying how space impacts employee experience and organizational dynamics. This information is summarized in tables 1-3. The Atlanta office is the largest, spanning 31,500 square feet and housing 175 employees across two floors connected by an atrium. In contrast, the Charlotte office is significantly smaller, covering 7,500 square feet, with 25 employees. Durham, housing the same number of employees as Charlotte, offers slightly more space per person in just over 11,0000 SF. The Washington DC office, with 65 employees, occupies approximately 14,300 square feet. The offices also vary in their outdoor space offerings. The Atlanta and Charlotte offices feature dedicated outdoor terraces directly accessible from the workspace, while the Washington DC office has access to a shared rooftop terrace three floors above the office. The Durham office, although lacking private outdoor space, provides tenants with access to a public plaza in front of the building.

Table 1, Population and Population Density of Study Cities (Data from US Census Bureau, 2020)

| | Atlanta | Charlotte | Durham | Washington DC |
|---------------------------|-----------------------|-----------------------|-----------------------|------------------------|
| Population (2020) | 500,000 | 898,000 | 291,000 | 672,000 |
| Population Density | 3,685/mi ² | 2,837/mi ² | 1,484/mi ² | 11,535/mi ² |

Table 2, Area and Population of Study Offices

| | Atlanta | Charlotte | Durham | Washington DC |
|-----------------------|----------------|------------------|---------------|----------------------|
| Area (SF) | 31,500 SF | 7,500 SF | 11,044 SF | 14,317 SF |
| # of Employees | 175 | 25 | 25 | 65 |
| SF/person | 180 SF/person | 300 SF/person | 442 SF/person | 218 SF/person |

Table 3, Building Features and HVAC Systems of Study Offices

| | Atlanta | Charlotte | Durham | Washington DC |
|--------------------------------|------------------------------------|----------------------------|--|------------------------------------|
| Building Age | 1985 | 2000 | 1965 | 1928 |
| Significant Renovations | 2010 | 2021 | 2019 (HVAC) | 2021 |
| Number of Floors | 6 | 23 | 15 | 5 |
| HVAC System Type | Radiant w/ DOAS | VAV | VAV | VAV |
| Fresh Air | 100% OA | % OA | 30-100% OA | 5 CFM/person |
| Air quality | - | - | Ionization System | UV filtration |
| Air Intake Location | Roof | Roof | Roof | Roof |
| Air Filters | MERV 13 | MERV 13 | MERV 13 | MERV 13 |
| Temperature Setpoint | 70/72 °F | 70/75 °F | 72 °F | 70/75 °F |
| Smoking Policy | No smoking allowed on the premises | No Smoking within building | No smoking within 100 feet of building | No smoking allowed on the premises |
| Building Certifications | LEED Platinum | - | WireScore Certified | LEED Gold (Core and Shell) |

B. Building and HVAC descriptions

Each location was thoughtfully designed to prioritize both occupant health and building performance, featuring expansive glazing with urban views, indoor plants, and low emitting materials. The offices all include open, benched workstations with several enclosed conference rooms, team workspaces, and focus areas. The Atlanta office occupies two floors in the building (floors 5 and 6) which are connected by an atrium, however sensors were only installed on the fifth floor, which had the greatest density of occupants. Additionally, each office features a communal kitchen and breakout areas for employee use. Following company policy, the design of each office emphasized a high-quality, healthy space, specifying low/no VOC finishes.

The four study office locations each feature unique building characteristics and HVAC systems tailored to their respective environments. While the Charlotte, Durham, and Washington DC offices utilize traditional variable air volume (VAV) systems, the Atlanta office stands out with its radiant mat system in the ceiling for thermal conditioning and a dedicated outdoor air system (DOAS) for ventilation. This innovative approach was made possible because the company under study owns the building, whereas the other offices rent. As a result, the firm describes this building as a “living lab” and educational tool, implementing several advanced features, including the sophisticated HVAC system. The DOAS draws fresh air from a rooftop unit, utilizing an energy recovery wheel, and distributes it through an under-floor air distribution (UFAD) system, which tenants cannot adjust. This unconventional setup posed challenges, particularly since the building engineer was new to this site at the start of the study, leading to some issues that will be addressed later. Although the building’s marketing materials highlight the presence of a CO₂ monitor, the building engineer mentioned that, if installed, it had not triggered any alarms, and its exact location was unknown to him. Despite these challenges, the building achieved 58% cost reduction in energy when renovated in 2010 and received a 2012 AIA Committee on the Environment (COTE) Top Ten Award.

In Durham, a recent \$7.5 million HVAC upgrade was completed while tenants remained in place, resulting in a 40% energy savings in 2022. The building manager has serviced the building for 30 years and is incredibly knowledgeable about the systems. The upgraded HVAC system can provide up to 100% outdoor air (OA) with an economizer under favorable conditions, with a minimum 30% OA. Ionization systems were also installed in the air handler units (AHUs) during the renovation to help enhance air quality.

since 2016 when wildfires were burning in Western North Carolina (Lee et al. 2023). In Washington DC, a “code purple” alert was issued in June 2023 and all outdoor activities, including recess, outdoor classes, athletic practices, and competitions were canceled in all Washington DC public schools (Office of the Mayor 2023).

Of the four cities studied, Durham had the highest percentage of ‘good’ air quality (AQI <50) in 2023 at 70%, likely because it is not as densely populated as the other cities, as shown in Table 1, and has limited industrial activity. In contrast, while air quality in Washington DC has improved significantly over recent decades, it still experiences pollution from high population density, traffic congestion, and industrial activity. Despite being the most densely populated city in the study and experiencing the most significant impact from the Canadian wildfires in 2023, Washington DC had the second highest air quality in 2023 with 43% ‘good’ AQI. Following closely behind was Charlotte at 40%. Like its North Carolina counterpart, Charlotte typically has

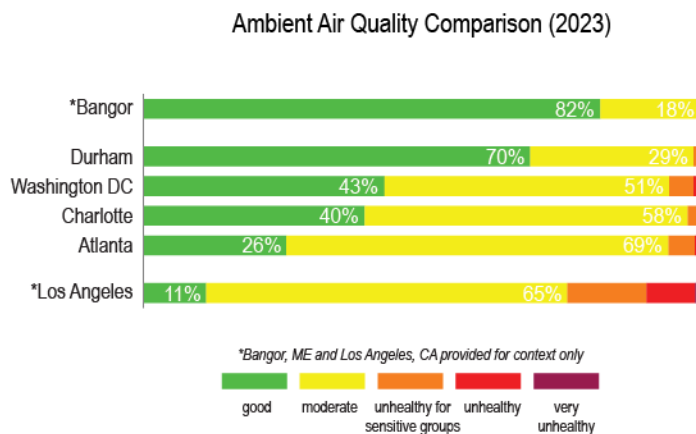


Figure 7, Summary of Ambient Conditions in 2023
Data from US EPA, Daily AQI by CBSA

good air quality but is significantly denser than Durham and can be impacted by pollution from traffic, industry, and nearby power plants. Finally, Atlanta emerged as the city with the lowest air quality rating among the four, with only 26% of days in 2023 recorded as ‘good’. This can likely be attributed to Atlanta’s unique topography, characterized by a bowl-like shape surrounded by mountains, which can lead to stagnant air which can more easily trap pollutants (Friberg et al. 2017). For further context, Figure 7 compares the AQI of these cities against that of Bangor, Maine, and Los Angeles, California, representing the best and worst air quality extremes in the United States. This broader comparison helps elucidate the varying degrees of air quality among

the study cities, underscoring the localized factors influencing their respective air quality profiles.

D. Indoor air monitoring

Indoor air quality (IAQ) data was recorded using multiple Kaiterra Sensedge Mini sensors in each office, capturing measurements of PM_{2.5}, PM₁₀, tVOC, CO₂, temperature, and relative humidity, at 15-minute intervals. Technical specifications can be found in Supplementary Materials (Table 8). Data was collected continuously for eleven months, spanning October 20, 2023, to September 21, 2024. The study adhered to the Performance Verification protocol for sensor data as specified by the WELL Building Standard to the extent possible. Sensors were installed within the breathing zone (3.6 – 5.6 feet above the floor), at least 3.3 feet from walls, doors, windows, air supply or exhaust outlets, air purifiers, or other potential influences (humidifiers, cleaning supplies, printers, photocopiers) (IWBI 2022). According to WELL guidelines, one sensor is required for every 3,500 square feet, with a minimum of two sensors for spaces smaller than 35,000 square feet. Due to budget constraints, however, only the minimum number of sensors was installed - one in the primary work area and one in the communal kitchen. The Washington DC studio was an exception, having four sensors already installed, including additional units in the entryway and main conference room. Building occupants in all four offices could access live data through an online dashboard on the Kaiterra website, which provided real-time IAQ values and rated both indoor and outdoor air quality as ‘good’, ‘moderate’, or ‘poor’. Sensors were validated at both the start and end of the study following manufacturer guidelines.

Measured data was compared against Kaiterra’s 2023 report, “State of Indoor Air Quality”, which analyzed air quality data from 4,294 sensors globally in 2022. While this report is currently the sole benchmark for workplace air quality, it has some limitations. Data was collected from existing Kaiterra clients, who are likely to be more attentive to air quality than average building operators, potentially leading to more favorable results. Additionally, the report does not specify how many sites were operating at full occupancy during a period where many businesses were adjusting to post-pandemic conditions and increased remote work. Kaiterra has noted that this study provides preliminary data for reference purposes only and should not be used for anything other than comparative analysis. Despite these limitations, the Kaiterra report

serves as the only available benchmark and is used selectively in this paper for comparative baseline conditions.

Table 4, Evaluation metrics defined by Kaiterra for indoor air

| | Good | Moderate | Poor |
|-------------------------|----------------------------|-----------------------------------|----------------------------|
| PM_{2.5} | < 12 µg/m ³ | 12 – 35 µg/m ³ | > 35 µg/m ³ |
| PM₁₀ | < 55 µg/m ³ | 55 – 155 µg/m ³ | > 155 µg/m ³ |
| tVOC | < 1005.5 µg/m ³ | 1005.6 – 3016.7 µg/m ³ | > 3016.8 µg/m ³ |
| CO₂ | < 750 ppm | 750 – 900 ppb | > 900 ppm |

E. Semi-structured Interviews

In the fall and spring, eighteen and twenty self-selected participants were interviewed, respectively, with an even balance of male and female employees. Recruitment was conducted through emails sent by an internal contact and postcards placed on desks at the beginning of each study period. Participation was voluntary, with no direct influence from company leadership on participant selection. Each site offered two interview options during each season – one in person and one remotely via Zoom. Participants scheduled 20-minute interviews on designated days using the Calendly online scheduling tool. Consent was obtained from each interviewee, and interviews were audio-recorded for transcription purposes.

The fall interviews were semi-structured, featuring a consistent set of fourteen questions designed to understand the employee’s experiences and perceptions of their workplace environment, with a focus on physical space and access to the outdoors. Based on the analysis of the fall responses, the spring interviews included eleven new questions aimed at exploring employees’ relationship with nature in the workplace. The full list of questions from the spring interviews can be found in the Appendix B.

Quantitative Results

A. Temperature and Humidity

During working hours (8 AM – 6 PM), the four study offices maintained consistent indoor conditions regardless of fluctuating outdoor weather. Throughout the year, each office

held a consistent average indoor temperature in the low-to-mid 70's (°F). The overall average temperatures (across all seasons) show that the Washington DC office is the warmest (75.1°F), followed by Atlanta (74.2°F), while Charlotte (73.0°F) and Durham (72.2°F) are slightly cooler. This data is summarized in Table 5. In contrast to outdoor conditions, all four offices had a cooler average temperature in the summer than in winter. The winter data saw the greatest variability, particularly in Atlanta and Washington DC, where temperatures peaked at 80.9°F and 78.2°F respectively. Washington DC experienced a 9.5°F temperature range during the winter while Atlanta had an even wider range of 10.8°F temperature range in the winter and 10.0°F in the spring. The radiant conditioning system in the Atlanta office poses challenges for rapid temperature adjustments, leading the building manager to preemptively lower the temperature before larger meetings or events to offset the added body heat from occupants. Summer, on the other hand, was marked by significant consistency across all offices. For instance, in Charlotte, the temperature range was only 1.9°F (70.8°F to 72.7°F) compared with a 6.6°F range in the winter (69.0°F to 75.6°F)

Similarly, the offices maintained a tight range of indoor humidity levels, with each office averaging in the 30-40% range. Charlotte stood out with the highest humidity levels, particularly in the spring and summer, reaching a maximum of 55%. In contrast, Durham displayed the widest range of humidity levels, particularly in winter, dipping to a low of 17%, well below the EPA's recommended range of 30-60% (US EPA 2014). Despite this, summer humidity was consistent within all offices, with Charlotte showing the most stability. On average, Charlotte maintained the highest average relative humidity (40.9%), followed closely by Atlanta (40.7%), while Durham (37.2%) and Washington DC (36.3%) were relatively drier. This data is summarized in Table 6.

Table 5, Measured Temperature (°F)

| | Atlanta | | | Charlotte | | | Durham | | | Washington DC | | |
|----------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|---------------|-------------|-------------|
| | min | max | av. | min | max | av. | min | max | av. | min | max | av. |
| Fall | 71.5 | 76.0 | 74.0 | 71.5 | 78.0 | 74.6 | 68.8 | 73.8 | 71.7 | 73.2 | 77.7 | 75.7 |
| Winter | 70.1 | 80.9 | 75.1 | 69.0 | 75.6 | 72.7 | 71.2 | 75.6 | 73.1 | 68.7 | 78.2 | 74.6 |
| Spring | 71.9 | 81.9 | 75.6 | 71.4 | 74.8 | 73.0 | 69.7 | 75.0 | 71.7 | 71.9 | 79.8 | 75.8 |
| Summer | 69.3 | 74.7 | 72.1 | 70.8 | 72.7 | 71.7 | 70.5 | 74.9 | 72.3 | 72.2 | 76.5 | 74.1 |
| AVERAGE | 70.7 | 78.4 | 74.2 | 70.7 | 75.3 | 73.0 | 70.1 | 74.8 | 72.2 | 71.5 | 78.0 | 75.1 |

Table 6, Measured Relative Humidity (%)

| | Atlanta | | | Charlotte | | | Durham | | | Washington DC | | |
|----------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|---------------|-------------|-------------|
| | min | max | av. | min | max | av. | min | max | av. | min | max | av. |
| Fall | 20.9 | 47.0 | 36.2 | 20.5 | 51.9 | 37.1 | 20.7 | 52.0 | 35.3 | 28.7 | 46.7 | 35.1 |
| Winter | 32.2 | 49.3 | 40.1 | 20.6 | 50.6 | 30.5 | 16.6 | 48.0 | 27.8 | 23.2 | 45.2 | 28.0 |
| Spring | 27.4 | 49.0 | 40.1 | 31.4 | 51.3 | 42.7 | 25.5 | 47.3 | 41.2 | 21.7 | 52.2 | 36.2 |
| Summer | 43.2 | 49.6 | 46.4 | 49.5 | 55.2 | 53.3 | 41.0 | 50.6 | 44.5 | 37.4 | 52.4 | 45.9 |
| AVERAGE | 30.9 | 48.7 | 40.7 | 30.5 | 52.2 | 40.9 | 25.9 | 49.5 | 37.2 | 27.7 | 49.1 | 36.3 |

B. Indoor Air Quality

Considering the wide range of variables present in the four study offices, directly comparing individual air quality metrics between them may not fully capture their unique conditions and challenges. To address this, Figure 8 illustrates the seasonal variations in indoor air quality for each office location over the entire season², providing a more comprehensive view than the two-week study period alone. Kaiterra’s qualitative assessment is used to display the percentage of time air quality falls in the ‘good’, ‘mediocre’, or ‘poor’ categories, based on the ranges shown in Table 4. By averaging this qualitative assessment, it offers a broader perspective on air quality, focusing on the overall distribution of air quality levels over time rather than comparing specific metrics to a fixed standard. The specific data is described more completely in a separate paper on the study. With minor adjustments, each of these offices could easily meet the stringent criteria set by the WELL Building Standard, which emphasizes the importance of creating indoor environments that support the health and well-being of occupants.

The Atlanta office experienced a notable failure of building management during the winter, leading to the exclusion of winter data from the yearly summary shown in Figure 8. This exclusion was made to ensure a more accurate representation of normal HVAC operating conditions. The Atlanta office relies on a rooftop DOAS unit for fresh air, which uses water coils to temper the air. However, these coils are susceptible to freezing when ambient conditions drop below 34°F. In January, when overnight temperatures fell into the low teens, the fresh air damper automatically closed to protect the coils from freezing, requiring a manual reset. Two months later, in March, when temperatures reached 80°F for the first time that year, staff reported to the

² Note that for fall, data collection began on October 20 rather than September 21.

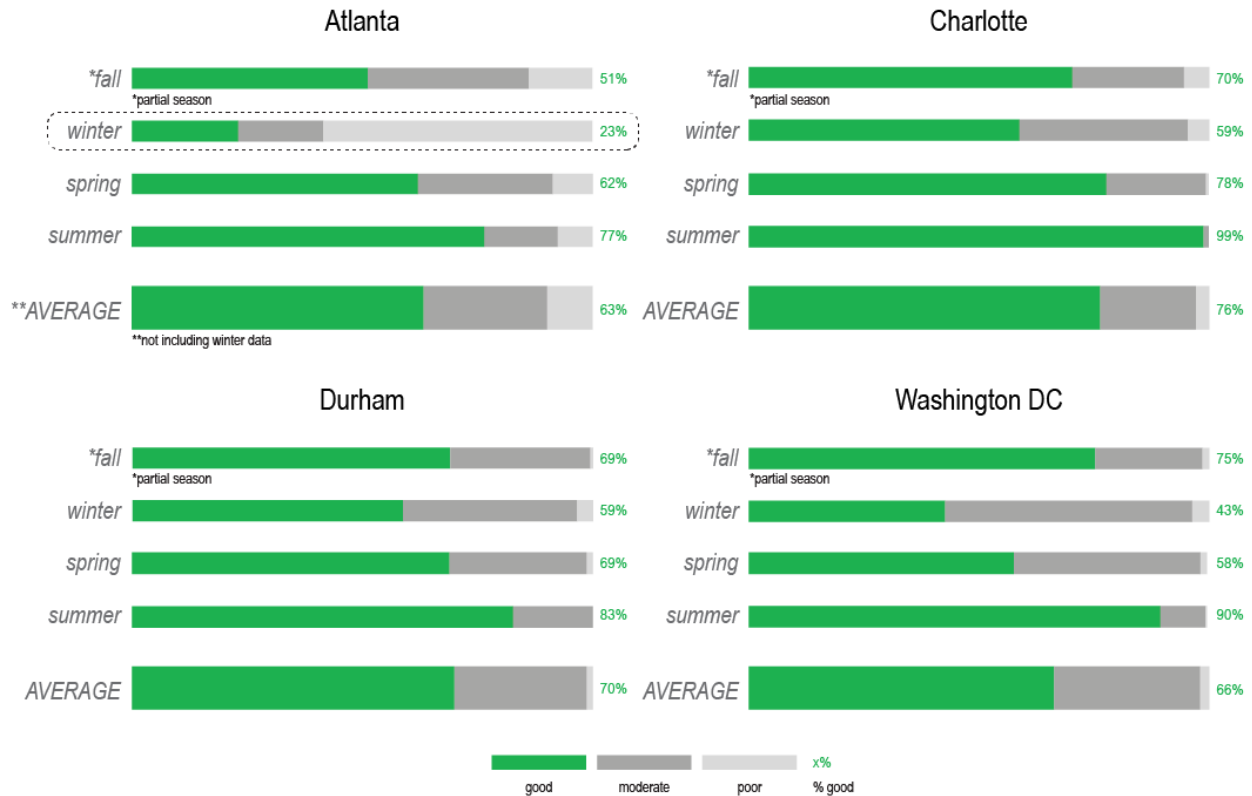


Figure 8, IAQ by season

building manager that the indoor environment was uncomfortably hot and stuffy. Investigation revealed that the DOAS air damper remained closed, meaning that no fresh air was provided to the building from January 17 – March 14. This incident highlights a significant failure in building management, which is unfortunately a common challenge encountered with advanced systems where engineers may lack sufficient expertise to manage complex systems effectively. During the period when the damper was closed, CO₂ levels significantly exceeded recommended thresholds, with readings surpassing 2,000 ppm on several occasions. This incident serves as a valuable case study for future research, highlighting the essential role of effective building management and proper fresh air ventilation in regulating indoor air quality.

During working hours, average CO₂ levels in the four study offices were generally below baseline concentrations, with Atlanta at 571 ppm, Charlotte at 511 ppm, Durham at 450 ppm, and Washington DC at 515 ppm. While CO₂ levels did occasionally surpass 900 ppm in Atlanta in Washington DC, overall ventilation systems appeared to be effective. Particulate matter levels (PM_{2.5} and PM₁₀) were consistently low across the offices, indicating effective filtration and minimal internal pollution, though Durham and Atlanta showed slightly higher averages. The

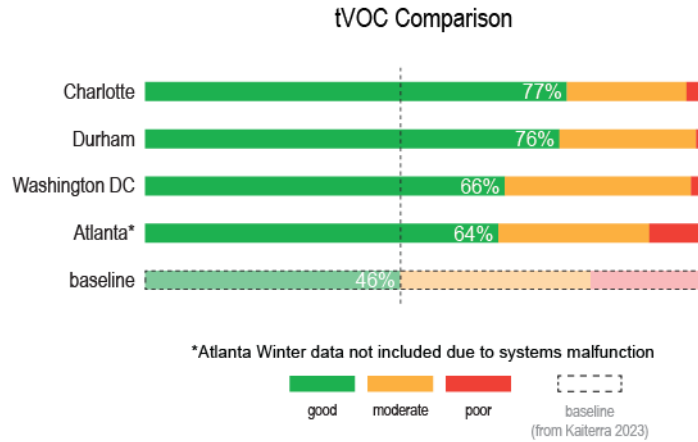


Figure 9, tVOC comparison during business hours (full study)

Washington DC office had occasionally high PM_{2.5} levels, particularly during non-working hours. Although some areas may require improvement, the air quality in these offices reflects a strong commitment to maintaining healthy indoor environments.

While the company has implemented high-quality ventilation practices uses low-emitting materials, each site experienced challenges in managing peaks in tVOC concentrations, indicating issues related to interior sources. While all four offices fell beyond the WELL prerequisite threshold of 500 µg/m³, their tVOC levels were still significantly below the average concentrations reported in Kaiterra’s “State of Indoor Air Quality” report, which found that buildings in the Americas averaged at 6,050.7 µg/m³ during working hours. This indicates that most buildings in the United States struggle to manage tVOC concentrations. According to the Kaiterra study, average conditions were considered ‘poor’ in the Americas, as well as Asia Pacific (APAC) and Europe/Middle East (EMEA). TVOC levels only reached ‘good’ status for 45.9% of the year in the Americas, and 46.2% globally (Kaiterra 2023). In contrast, as illustrated

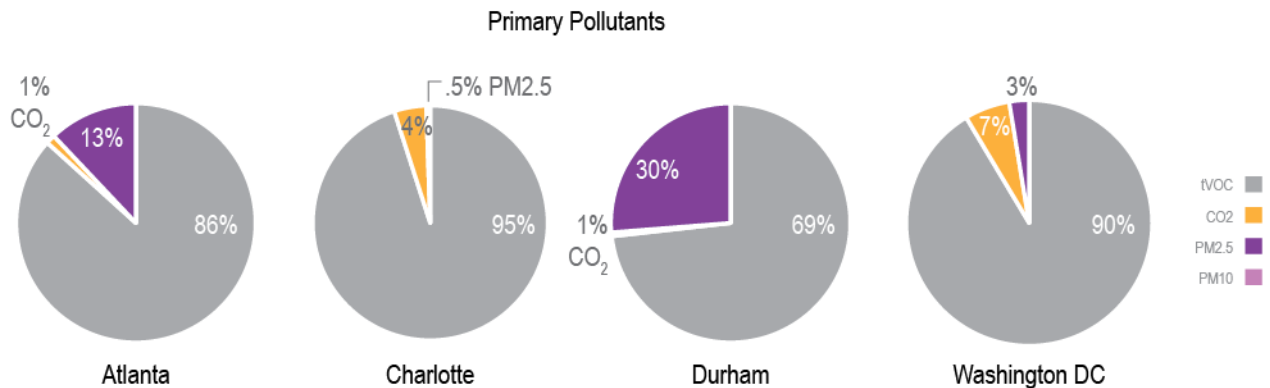


Figure 10, Primary pollutant during fall and winter study periods (working hours)

in Figure 9, tVOC levels in Charlotte were good for 77% of the year, 76% in Durham, 66% in Washington DC and 64% in Atlanta with average workday values of 697 $\mu\text{g}/\text{m}^3$ in Charlotte, 800 $\mu\text{g}/\text{m}^3$ in Durham, 1,044 $\mu\text{g}/\text{m}^3$ in Washington DC and 2,646 $\mu\text{g}/\text{m}^3$ in Atlanta. Though these values fall well above Kaiterra's observed baseline condition, tVOC concentrations emerged as the primary concern across all four study offices as other contamination sources were well controlled. Specifically, tVOCs were recorded as the primary pollutant for 86% of working hours in Atlanta, 95% in Charlotte, 69% in Durham, and 90% in Washington DC, as shown in Figure 10. $\text{PM}_{2.5}$ was the second most prevalent pollutant in Atlanta and Durham, while CO_2 was the second most prevalent in Charlotte and Washington DC.

C. Comparison of Indoor vs Outdoor Conditions

Using the same methodology and thresholds as the EPA's AQI Standard, Kaiterra has developed an overall indoor index value to provide a single snapshot of indoor air quality in a space while also identifying which pollutant to address first (Kaiterra). An index value is calculated for each indoor pollutant, with the highest value presented as the overall index. Though EPA's AQI value and Kaiterra's index value measure different pollutants and are not directly comparable, each provides an air quality rating *based on available information* for each condition. Currently, these metrics are the only means of categorically assessing and comparing the quality of indoor and outdoor air. Additionally, while the EPA regulates a municipality's air quality through the AQI value, no standard or regulatory metric currently exists for indoor air. Figure 11 uses these indices to compare the quality of indoor and outdoor air during each season.

Contrary to the common belief that outdoor air is more polluted than indoor air, this was not always true, even for four spaces with above average IAQ metrics. Washington DC, for example, is often perceived as having poor air quality due to its high density and urban pollution, but actually had better outdoor air quality compared to indoor air during three of the four study seasons - fall, winter, and spring. The city's outdoor air had a lower AQI than the indoor index for more than half of the working hours, suggesting generally better air quality outside. Although Atlanta is known for poorer ambient air quality compared to the other cities in the study, the difference between indoor and outdoor air quality was minimal. In fall and spring, indoor air had a higher index value than outdoor air for nearly half of working hours at 48% and 46%, respectively. However, during the winter study, due to poor building management, indoor air

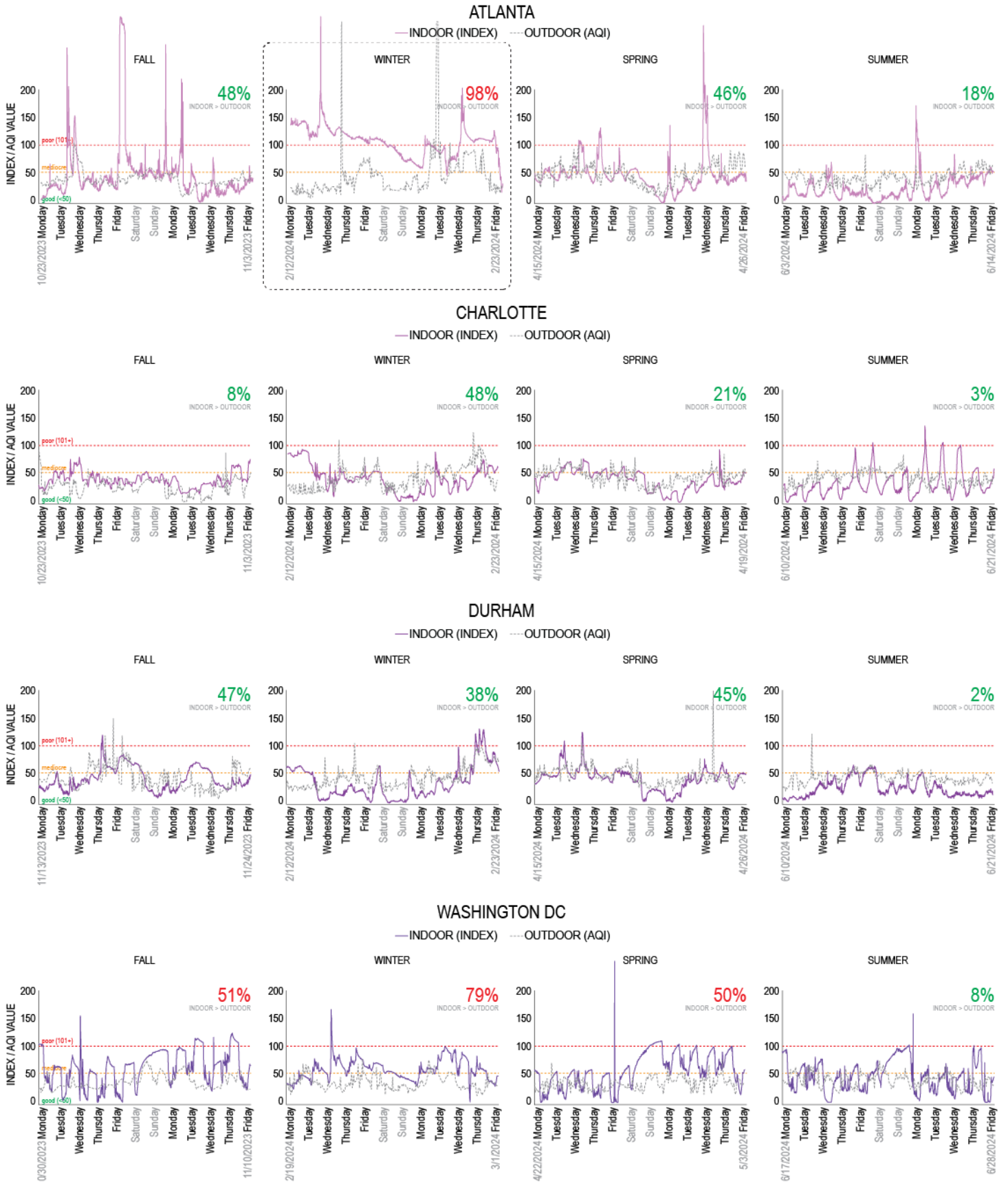


Figure 11, indoor vs outdoor air quality comparison

was significantly more polluted than outdoor air for 98% of working hours. This stark contrast highlights the need for closely monitoring indoor air quality, especially during renovations or similar activities. Although the average AQI in each city did not significantly increase during the summer, except in Washington DC, each office experienced improved air quality in the warmest season, resulting in less time when indoor air was worse than outdoor air. In all offices, except Atlanta which has a dedicated ventilation system, the increased conditioning load led to better ventilation, improving indoor air quality. Overall, indoor air was worse than outdoor air for roughly one third (34%) of working hours. It is also important to note that these buildings are higher performing than typical urban office buildings, so the ratio of time indoor air is cleaner than outdoor air would likely shift in the standard office environment. Having established that outdoor air is not as detrimental as often perceived, and that indoor air quality may be worse than anticipated, this study will now investigate the reasons behind occupants' continued perception of indoor environments as significantly healthier compared to outdoor settings.

Qualitative Results

Perceptions of air quality and indoor health are shaped by a complex interplay of environmental conditions, personal experiences, seasonal variations, external information, and other contextual factors. This section draws on qualitative data from semi-structured interviews to reveal how building occupants assess air quality in workplace settings. The interviews were carried out in two phases, with the questions in the second round specifically designed based on the responses from the first round undertaken in the fall. This paper primarily focuses on the second round of interviews, which took place in the spring, while also incorporating responses from the first round to provide additional context.

During the first round of interviews, participants at all four offices were asked, "Which condition do you believe to be healthier, inside or outside?" an overwhelming majority (71%) of participants said **outside was healthier**, largely citing the mental health benefits of connecting with nature. These responses align with research suggesting that outdoor environments serve as a vital outlet for stress relief and mental rejuvenation (Park et al. 2010; Ulrich et al. 1991; Kaplan 1992; Bratman et al. 2019). However, when the question shifted specifically to air quality during the spring interviews, a more nuanced perspective emerged. When asked, "In [city], do you believe the air in your office to be healthier than outside?", 80% of respondents said **inside air**

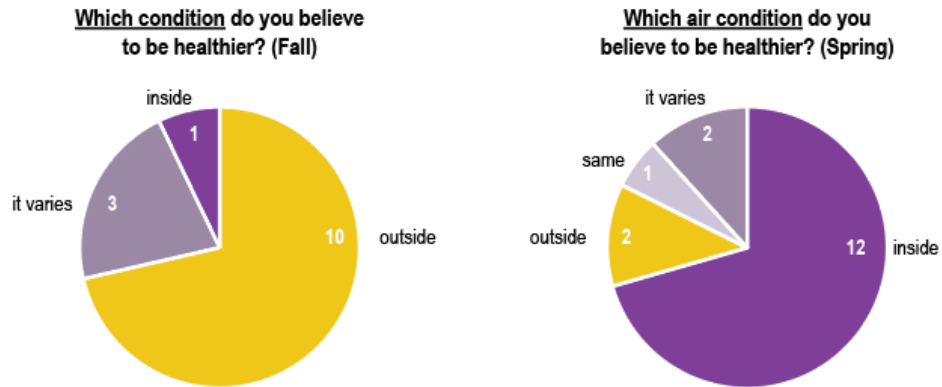


Figure 12, difference between fall and spring interview responses

was healthier. This significant discrepancy, illustrated in Figure 12, resulted from a simple reframing of the question and reveals that perceptions of air quality in workplace settings differ from the broader views of environmental health and nature, suggesting that distinct criteria are used to evaluate each. In response, this section will explore the underlying drivers of air quality perceptions observed in these four urban office buildings.

Since the metrics used to define “health” were not explicitly stated in either interview question, respondent’s apparent interpretation of the term varied. In the fall interviews, psychological considerations played a significant role in shaping responses, with participants describing their time outdoors as refreshing, invigorating, and essential for maintaining a positive mindset (McCormick et al. 2024). However, when the focus shifted specifically to air quality, respondents began to consider the technical aspects of health, such as the presence of pollutants, allergens, and other contaminants. This shift revealed a growing concern for protection against outdoor forces, leading many to view indoor environments – characterized by controlled conditions, air filtration systems, and protections against outdoor pollutants - as healthier. Despite the common perception that indoor air is superior, driven by concerns about pollutants and the benefits of technological interventions, it is necessary to understand the underlying reasons for these beliefs in order to provoke alternative models of workplace design. When participants were asked to explain their choices in more detail, their responses revealed three primary themes that shed light on their perceptions: (1) trust in technology, (2) distrust of cities, and (3) a general lack of knowledge about indoor air quality.

A. Trust in technology

Numerous respondents expressed a deep confidence in the effectiveness of indoor HVAC technologies to eliminate outdoor pollutants, particularly through filtration and air purification systems, promising clean and healthy indoor air. Based on interview data, a theme of trust in mechanical systems emerged from various factors such as the sense of control and predictability, perceived cleanliness, protection from pollutants, and the psychological comfort their presence instills. Participants perceived these systems as representing a more dependable and consistent indoor environment, in contrast to the unpredictable and variable conditions experienced outdoors. This trust in technology is reflected in the following responses:

There might be a slight edge to inside just because of human intervention with air purifiers and stuff. (A3)

I would just assume since we have a newer building and newer systems and maintenance with the filtration changing out filters in a high-end system that it would be pretty good. (A4)

I know from a technical standpoint in the modern building, the air inside is probably cleaner only because if it's being recirculated, it's going through filters. (DC1)

Because we know that we can create a more controlled environment, and it can be a healthier air environment through systems and architecturally enclosed space. (D4)

I remember being surprised that our indoor air is better than the outdoor air. I guess that makes sense given that it's going through filtration. (D4)

I think it's healthier [indoors] from what they tell you when you tour the office. Yeah, inside, like all the filters and things. And all the plants, I think that also helps. (DC3)

There was a general belief that modern buildings with updated systems and regular, visible maintenance contributed to better air quality. Similarly, older buildings with potentially outdated or poorly maintained HVAC systems were associated with lower quality indoor air. For example, one Durham respondent suggested that “it’s healthier outside because this is kind of an older building, and I don’t know how up kept the mechanical systems are or anything like that” (D2), unaware that the building had undergone a major HVAC upgrade only two years prior. Additionally, perceptions of air quality were influenced by the visibility and perceptibility of ventilation practices. As one participant noted, “feeling fresh might be different from actual freshness. Right now, I think the only ventilation is through floor units. So, if that was more

visible and perceptible that might make it more legible” (A1). This highlights the importance of making ventilation systems, whether mechanical or natural, more noticeable to reinforce their effectiveness and improve user confidence in air quality. Ultimately, the belief that modern buildings ensure better air quality persists, highlighting how assumptions about building age, maintenance patterns, and visibility of systems shape perceptions of air quality.

While the appeal of controlled environments and advanced mechanical systems often instills confidence in the quality of indoor air, this belief is grounded in what Nancy Lankton, a scholar of trust for emerging technologies, refers to as ‘system-like trust constructs’ such as helpfulness, reliability, and functionality (Lankton et al. 2015). These constructs assure users that technologies like HVAC systems, filters, and air purifiers will reliably perform their intended tasks and maintain high air quality. These constructs are based on the tangible performance and operational consistency of the technology, rather than on interpersonal qualities or ‘human-like trust constructs’ such as benevolence, integrity, and ability, which are more about personal relationships and ethical considerations (Lankton et al. 2015; Mcknight et al. 2011). This distinction is important because it highlights how users’ confidence in technology is shaped by their expectations of consistent performance and functionality, rather than by perceived personal qualities of the technology itself. However, this trust can be fragile. During the COVID-19 pandemic, for example, workers became wary of returning to offices, questioning whether these same systems could effectively protect them from viral transmission. This complexity reflects a growing awareness that while technology can enhance indoor air quality, there remains an inherent unease about the limitations of such systems in addressing broader environmental concerns.

In response to the question, “How would you make the air feel more ‘fresh’ in the office?”, however, responses revealed a notable shift away from the dependence on technological solutions. Instead, participants expressed a strong preference for spaces that felt less regulated and more connected to the outdoors. Several participants articulated a desire for the simple pleasure of opening a window and experiencing a natural breeze, as reflected in comments such as, “I love when I get to my house and open windows and let cross ventilation in, and you feel renewed in your house. You feel like all the smell of people goes away” (D5). This indicates a desire for the refreshing effect of natural airflow and the psychological benefit of a more dynamic environment. Similarly, when discussing ways to enhance outdoor access in the

workplace, respondents preferred approaches that promoted open, natural environments over purely technological interventions. One respondent expressed a desire for “an office patio full of green stuff on the porches and like little gardens outside. That’s where I want to stay even if the weather is a little bit hotter or colder, rather than stay inside” (C3). Another respondent articulated a desire for spaces that “create different types of ecosystems” (A2), suggesting a preference for environments that offer varied and dynamic natural settings. Additionally, there was a strong inclination toward integrating outdoor amenities with the indoor environment, effectively blending the two and creating cohesive, extended workspaces. These findings suggest a growing trend toward appreciating natural, less controlled environments in the workplace. Rather than relying solely on technological solutions to manage air quality and comfort, building occupants are increasingly seeking simpler, more organic approaches to enhance well-being and productivity.

B. Distrust of cities

With this trust in mechanical systems came an underlying suspicion towards the uncontrollable and unpredictable nature of the outdoor environment. Respondents’ concerns about outdoor pollutants, particularly in densely populated urban areas, reflect a broader societal awareness of the potential health risks associated with environmental pollution. References to heavy traffic, construction activities, and industrial emissions represent the diversity of tangible outdoor pollution sources that contribute to ambient air quality concerns. The discrepancy between the perceived cleanliness of indoor environments and the pollution outside is emphasized in several notable responses. For example, a participant from the Atlanta office highlighted the contrast between indoor and outdoor air quality, stating, “Definitely in the office is healthier, just because there’s so much smog and pollen and all kinds of stuff in the air around here, especially in an urban setting” (A2). Similarly, a respondent from the Durham office noted the visible signs of pollution outside compared to the perceived cleaner indoor environment, stating, “I just feel like there’s so much construction and everything happening out there, so I can actually see the smoke and the fumes and stuff like that... and I don’t feel that in here” (D1). Other respondents echoed these concerns, describing how urban environments impact their perception of air quality:

Every time I walk into Uptown it has different smells and maybe is not as clean as you would think. (C4)

If this office is located in New York or somewhere where the cars come and go, where the toxic air is polluted, having the barriers, having the filters in the air, it helps with better health. It depends on where the office is located. (C3)

I can imagine, even if it's not too much, places like Atlanta or DC, where there's way more traffic, way more urbanized zones and chaotic atmospheres that can increase and be different. (D5)

Well, because it's Atlanta, a lot of cars outside, a lot of pollution. (A5)

There's a different sense of freshness going that way with less cars passing you, so I guess it would depend on where you're talking outside in general. And the patio also overlooks such a busy street so sometimes that's deceiving too. It feels fresh, but you also have all that right below you. (A5)

It really depends on where you are. If you're right by a road, I would say indoor. If you are somewhere where there's not a lot of direct pollutants, I would say outdoor. (A4)

Participants did recognize the seasonal variation in air quality, particularly in relation to allergens and pollutants that are more prevalent outdoors during certain times of the year. This underscores the dynamic nature of air quality perceptions and the factors influencing them. Historical and cultural factors will also influence perceptions of urban environments. Negative associations with pollution, congestion, and industrialization in urban areas have been deeply engrained in societal narratives, shaping collective attitudes towards the healthiness of cities (Curtis 2007; Pinter-Wollman et al. 2018; Hoy 1996; Cori et al. 2020). Distrust of urban, outdoor air grew from concerns of health effects from respiratory diseases like tuberculosis and pneumonia, as well as coal-driven pollution. Seasonal changes in air quality and sensory responses, combined with historical and cultural influences, shape perceptions of urban environments and reinforce longstanding concerns about pollution and the associated health risks of cities.

Individual buildings, with their more visible and controllable systems, are often seen as more reliable. In contrast, large-scale urban pollution is linked to institutional decisions, and the erosion of social trust in these institutions is linked to growing public concerns about health, safety, and environmental protection (Kasperson et al. 1992). As post-industrial Americans experienced improved living conditions and reduced risks from traditional hazards, their focus shifted to newer concerns, such as environmental pollutants and lifestyle-related health issues.