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PERSPECTIVE ARTICLE

Neuroinclusive workplaces and biophilic design: Strategies for promoting occupational health and sustainability in smart cities

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Abstract

This study aims to investigate the impact of biophilic design on occupational health and productivity, with a particular focus on addressing the needs of diverse populations, including the neurodiverse, during the post-pandemic return to work. With an estimated 15 – 20% of the global population considered neurodiverse, it is crucial to understand and accommodate their specific needs, such as those with attention-deficit hyperactivity disorder, autism spectrum condition, and learning disabilities. These individuals face increased occupational stress, necessitating the development of targeted strategies. The renewed interest in sustainability and employee well-being has led to a resurgence of biophilic design in the workplace. Grounded in the concept that humans possess an inherent inclination to affiliate with nature, the biophilic design integrates natural elements and art into the built environment. This integration has been found to reduce activity in the amygdala, promoting stress recovery, prolonged attention, and increased productivity among employees. To effectively acclimate neurodiverse individuals in the work environment, biophilic design should be complemented using extended reality (XR) technology supported by artificial intelligence. Virtual reality, in particular, has been shown to facilitate individuals' comfort in new workspaces, aid in self-assessments through biofeedback, and enable the adjustment of surroundings for self-regulation. Furthermore, biophilic design has the potential to promote sustainability in smart cities by integrating natural elements into the built environment. This integration helps reduce the carbon footprint of buildings and enhances energy efficiency. By creating workplaces that prioritize biophilic design principles, organizations can contribute to a more inclusive, sustainable, and productive work environment.

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1. Introduction

The concept of biophilia was initially introduced by social psychologist Erich Fromm in 1964 and subsequently gained prominence through the work of biologist Wilson in the 1980s (Hartig *et al.*, 2011; Wilson, 1986). Wilson posited that increasing urbanization contributes to a growing disconnect from the natural world (Kellert & Wilson, 1995). The interdisciplinary applications of biophilia have since expanded, encompassing

fields such as biology, psychology, neuroscience, endocrinology, and architecture, all emphasizing the importance of reestablishing connections with nature and natural systems (Jha & Behera, 2022; Menezes *et al.*, 2021; Robinson & Pallasmaa, 2015). Incorporating natural elements into the design of built environments has been recognized as a means to also enhance mental health and well-being (Barbiero & Berto, 2021; Mazuch, 2017; Söderlund & Newman, 2017) (Figure 1). As such, biophilic office design emulates various aspects of the natural world, including the presence of water, light, and plants, as well as the utilization of botanical forms and curvilinear shapes that diverge from modernist trends (Kellert, 2008; Kellert *et al.*, 2011).

Biophilic design encompasses a range of elements that aim to integrate natural features and processes into the built environment (Table 1). These elements include natural light, which is achieved through abundant windows, skylights, and light wells, creating a connection with the outdoor environment, enhancing visual comfort, and supporting circadian rhythms (Kellert, 2008). Views of nature provide access to natural elements such as vegetation, landscapes, or water bodies, promoting relaxation, stress reduction, and cognitive restoration. Biomorphic forms and patterns, such as organic shapes and fractal patterns, mimic elements found in nature, evoking positive emotional responses and increasing visual interest (Kellert *et al.*, 2011). Integrating living systems, particularly indoor plants, not only improves air quality but also enhances well-being and fosters a sense of connection with nature. Using natural materials, such as wood, stone, and natural fibers, in building construction and interior finishes, evokes warmth and authenticity, creating a welcoming and harmonious environment. Water features, such as fountains or water walls, provide sensory stimuli and promote relaxation and tranquility. Thermal and ventilation variability, mirroring natural conditions with varying temperature and airflow,



Figure 1. Working in open office space, Royal Bank Tower, Montreal, 2017.

supports occupant comfort and well-being (Jha & Behera, 2022). Soundscapes incorporating natural sounds such as flowing water or birdsong create a soothing and calming environment while masking unwanted noise. Access to natural spaces, such as gardens or rooftop terraces, allows occupants to interact directly with nature. By incorporating these biophilic design elements, designers can create spaces that evoke the positive qualities of nature, improving well-being, enhancing productivity, and fostering a stronger connection between occupants and their surroundings (Söderlund & Newman, 2017).

The multifaceted nature of biophilic office design can have significant implications for the mental health and well-being of neurodiverse populations (Van der Geest, 2020). By adopting a neuroaffirming approach that emphasizes multisensory and multimodal environments, these spaces can better cater to the diverse sensory needs and preferences

Table 1. Elements of biophilic design

Biophilic design elements	Description
Natural light	Abundant windows, skylights, and light wells to bring in natural light, supporting circadian rhythms and enhancing visual comfort.
Views of nature	Incorporating views of vegetation, landscapes, or water bodies to provide access to natural elements, promoting relaxation, stress reduction, and cognitive restoration.
Biomimicry	Using organic shapes and fractal patterns that mimic elements found in nature, evoking positive emotional responses and increasing visual interest.
Living systems	Integrating indoor plants and other living organisms to improve air quality, enhance well-being, and foster a sense of connection with nature.
Natural materials	Using natural materials such as wood, stone, and natural fibers in building construction and interior finishes to create a welcoming and harmonious environment.
Water features	Incorporating water elements such as fountains or water walls to provide sensory stimuli, promote relaxation, and create a tranquil atmosphere.
Thermal and ventilation variability	Mirroring natural conditions with varying temperature and airflow to support occupant comfort and well-being.
Soundscapes	Integrating natural sounds such as flowing water or birdsong to create a soothing and calming environment while masking unwanted noise.
Access to natural spaces	Providing direct access to natural spaces such as gardens or rooftop terraces, allowing occupants to interact with nature.

of neurodiverse individuals (Motti, 2019). Furthermore, neurodivergent individuals often exhibit heightened sensitivity to visual stimuli (Dinishak, 2019). As such, incorporating views of nature and natural environments into office design can provide positive sensory experiences and promote well-being for these individuals (Aristizabal *et al.*, 2021). Moreover, achieving a balance between the body's sympathetic and parasympathetic nervous systems is essential for maintaining optimal health and well-being (Peterson *et al.*, 1988; Schumacher *et al.*, 2013). If environments are perceived by individuals as being stressful or chaotic, the sympathetic system is activated, eliciting a "fight-or-flight" response (Perry & Pollard, 1998). Simultaneously, the parasympathetic system is suppressed, disrupting the body's natural equilibrium and leading to mental fatigue and energy depletion (Adams & Kirkby, 2001).

Nature, as the primary habitat for humans, inherently fosters a state of homeostasis, which underpins approaches to biophilic design in general. The term *biophilia* originates from Ancient Greek and translates to "a love of living things" (Ashwell, 2010). This inherent connection to living organisms underscores the importance of integrating natural elements into built environments, particularly in office settings, where individuals spend a significant portion of their time. Furthermore, studies have found that 76% of the time spent in offices is in sedentary activities, such as sitting at a desk and typing; therefore, the health benefits are impactful on two levels (Parry & Straker, 2013). By designing biophilic office spaces that prioritize multisensory and multimodal experiences, a more inclusive environment is created that supports the physical and mental health and well-being of the general population, especially neurodiverse individuals (Requena, 2021). Through the incorporation of natural light, greenery, and calming visual stimuli, biophilic office design can help mitigate stress, encourage relaxation, and promote a sense of balance and harmony for individuals with varying sensory needs (Kellert, 2008).

Employee well-being and satisfaction is not the only motivating factor for adopting biophilic design in the industry. The implementation of neuroinclusive sensory elements and these design considerations in workplaces has proven to yield significant financial benefits. By investing just US\$40 per person per year in biophilic design elements, organizations can experience a productivity increase of up to US\$6,500 per person per year (Sander *et al.*, 2019). This substantial return on investment is supported by research demonstrating the positive impact of natural elements on employee performance and well-being (Pawar, 2013). Studies have also shown that

workers in biophilic environments are over 15% more productive and motivated compared to those working in sterile surroundings (Hähn *et al.*, 2021). Furthermore, employees in spaces featuring natural plants exhibit more than a 15% increase in creativity (Rai *et al.*, 2020). These enhancements in productivity and creativity translate into tangible financial gains for businesses and organizations.

In addition, biophilic office design has been linked to improved cognitive performance, with employees in biophilic-certified buildings scoring 26.4% higher on cognitive tasks than their counterparts in non-certified buildings (MacNaughton *et al.*, 2017). These spaces also lead to fewer "sick building" symptoms, with a reduction of over 30% reported (Hu *et al.*, 2022). Such improvements in overall health and well-being can result in reduced absenteeism and healthcare costs, further contributing to an organization's bottom line (Lerner & Stopka, 2016). Moreover, the benefits of biophilic office design extend beyond the workplace, with employees reporting better sleep quality on returning home at night (Boubekri *et al.*, 2014). The improvement in sleep quality, measured by wristwatches that track sleep patterns, highlights the holistic and long-term advantages of incorporating neuroinclusive sensory elements in office environments.

Therefore, investing in neuroinclusive biophilic office design not only enhances employee well-being and satisfaction but also results in significant financial benefits for organizations. By creating spaces that cater to the diverse needs of neurodiverse individuals, employers can maximize productivity, creativity, and overall performance, while also reducing absenteeism and healthcare costs. In order to benefit from biophilic design, the present study aims to offer valuable insights and actionable resources for industry leaders seeking to enhance the productivity, health, and creativity of their entire workforce while also capitalizing on the unique skillset of the neurodiverse community. By examining various biophilic design strategies, such as immersive spaces, multisensory immersion, escape spaces with natural boundaries and nooks, calming soundscapes, thermal and airflow variability, material connections with nature, wayfinding, natural lighting, and the incorporation of digital and bioart, this paper will provide a comprehensive understanding of how to create neuroinclusive office environments.

In addition to highlighting the benefits of biophilia in the built environment, it is essential to consider established design standards that guide the implementation of these principles. One such standard is the WELL Building Standard, which includes specific criteria related to nature and access to natural elements. Standards such as WELL V2 M02 Nature and Place and M09 Enhanced Access

to Nature emphasize the importance of incorporating biophilic elements into indoor spaces and ensuring easy access to nature for occupants (Nicolini, 2022).

Furthermore, the Environmental Information Criteria for window view design offers valuable guidelines for creating optimal views that enhance the connection with nature. These criteria consider factors such as landscape distance seen from window views, visual satisfaction, and the balancing of natural elements with other design considerations (Kent & Schiavon, 2022). By incorporating these design standards into the discussion, we can ensure a more comprehensive understanding of how biophilic design can be effectively implemented and aligned with established industry guidelines. Thereby striking a balance between the principles of biophilic design and established design standards, designers, architects, and practitioners can create spaces that not only enhance occupant well-being but also adhere to recognized benchmarks of sustainable and health-oriented design. This integration of biophilic principles with established standards will contribute to a more holistic and effective approach to designing spaces that prioritize human health, connection with nature, and overall occupant satisfaction.

In addition to focusing on the importance of biophilic design, it is essential to provide a clearer explanation of the high-level concepts introduced alongside it. Biophilic design goes beyond the mere inclusion of natural elements in the built environment. It encompasses various principles and approaches that aim to create spaces that promote human well-being, connectivity with nature, and sustainability. These concepts include but are not limited to the use of natural lighting, incorporation of plants and greenery, integration of natural materials, consideration of sensory experiences, and attention to spatial layout and wayfinding. Each of these elements plays a significant role in creating environments that enhance occupant health, productivity, and satisfaction. By understanding and effectively implementing these high-level concepts in biophilic design, designers, and architects can create spaces that truly harness the benefits of nature and contribute to a more sustainable and nurturing built environment.

By implementing biophilic design principles, this study aims to assist organizations in developing inclusive workspaces that cater to the diverse needs and preferences of all employees, fostering a supportive and productive atmosphere. In addition, this approach can play a crucial role in promoting sustainability efforts in smart cities by integrating natural elements into the built environment. By leveraging natural lighting, ventilation, passive heating and cooling techniques, as well as green roofs and living walls, the carbon footprint of buildings can be reduced

while simultaneously addressing urban heat island effects, improving air quality, and providing insulation. The recommendations derived from this study will contribute to the growing body of evidence on the benefits of biophilic design, empowering industry leaders to create workspaces that prioritize well-being, creativity, sustainability, and productivity, while embracing and harnessing the potential of the neurodiverse community.

2. Literature review

This study addresses a significant gap in the existing literature by investigating the impact of biophilic design on occupancy health and well-being, particularly in the context of workplace environments. Despite the growing interest in biophilic design and its potential benefits, there is a need for a comprehensive review of empirical evidence and a clearer understanding of the specific outcomes associated with its implementation. The aim of this study is to examine the psychological and physiological effects of biophilic design on occupants, assess its impact on productivity and job satisfaction, and explore its potential role in promoting sustainability in smart cities. The objectives include investigating stress reduction, improved cognitive functioning, and emotional well-being as psychological effects, evaluating productivity, creativity, and job satisfaction as workplace outcomes, and examining the potential for reducing the carbon footprint and improving energy efficiency in the built environment. Through this research, we aim to contribute to the current understanding of biophilic design and provide valuable insights and recommendations for creating healthier, more sustainable, and more productive workspaces.

The use of biophilic design principles to incorporate natural elements into building design has been recognized as a key contributor to human well-being for many years (Gillis & Gatersleben, 2015). In fact, when redesigning the first “modern” city beginning in 1853, the city planner under Napoleon III, Georges-Eugène Haussmann, insisted on the importance of green spaces for the health of citizens and believed that the city’s health was directly linked to the availability of parks and other green spaces (Gerger, 2012). The redesign thus incorporated the addition of large boulevards lined with trees and the creation of several large parks throughout the city. The emphasis on incorporating nature into urban design was a precursor to the modern biophilic design movement, which recognizes the benefits of nature for human well-being and seeks to integrate natural elements into the built environment, leading to major green spaces in nearly every major city, including Central Park in New York City and the eight Royal Parks in London (Chae *et al.*, 2014).

The concept of biophilic design continued in the *fin de siècle* and from modernist trends in art and architecture, such as Art Nouveau, which aimed to reconnect individuals with the natural world (Grady, 1955; Joye, 2011). Since then, research has confirmed that by incorporating elements such as water, light, and plants, as well as emphasizing botanical forms and curvilinear shapes, biophilic design principles are able to create an immersive and multisensory environment that enhances human health and well-being (Gierbienis, 2019; Gillis & Gatersleben, 2015). In fact, the impact of biophilic design on various aspects of human health and performance, including life expectancy, productivity, mental health, absenteeism, and eye fatigue, as noted in findings from studies from the German Institute of Global and Area Studies, Cardiff University, and Stanford University (Blackhurst, 2022; Jones, 2012).

One important aspect of these design elements Joye (2011) noted is the use of visual contrasts to enable gradual transitions between light and shadow, which can cater to the needs of diverse occupants in workplaces. For example, high-placed windows can allow natural light to penetrate into the space while limiting distracting views outward, and the use of shading devices can control the amount and direction of sunlight to create a comfortable visual environment, notably for a neurodiverse workforce (Marchi, 2013). Such design principles have also been found to reduce stress and anxiety levels among occupants, as well as increase productivity and creativity (Kellert *et al.*, 2008).

In addition to the visual elements, the inclusion of natural materials such as wood, stone, and water can also have a positive impact on human well-being (Gillis & Gatersleben, 2015). The use of natural materials not only enhances the aesthetic appeal of the space but also provides a connection to nature, which has been found to have a calming effect on individuals. Furthermore, the presence of indoor plants has been found to reduce stress levels and improve air quality, contributing to a healthier and more comfortable indoor environment (Lee *et al.*, 2011) (Figure 2). Research has only recently, however, begun to focus on the workplace with these organic additions and has previously looked at the benefits of other types of structures and the benefits of both mental and physical health (Table 2).

For instance, the physical health benefits of biophilic design have been investigated in studies such as that by Zare *et al.* (2021), where a use case in hospitals to promote patients' well-being and recovery had positive results. In the study, the designs of five hospitals in Australia, Singapore, and the United States were compared and considered the significant health dimensions influenced

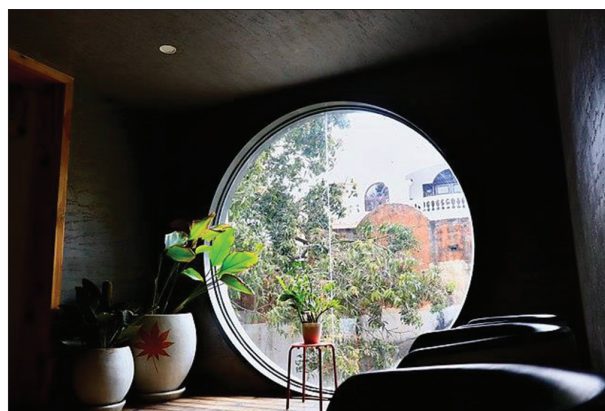


Figure 2. Guest seating and planter boxes inside an office, Filmnagar, Hyderabad, India, 2020.

Table 2. Mental and physical health benefits of biophilic design

Mental health benefits	Physical health benefits
Stress reduction: Exposure to nature and natural elements in the built environment promotes relaxation, reduces stress, and enhances overall well-being.	Improved air quality: Incorporating plants and natural ventilation systems helps improve indoor air quality, reducing the presence of pollutants and enhancing respiratory health.
Enhanced mood: Interacting with nature and natural elements elevates mood, reduces negative emotions, and increases positive feelings.	Increased physical activity: Access to green spaces and nature-inspired designs encourages physical activity, leading to improved cardiovascular health and reduced sedentary behavior.
Cognitive restoration: Views of nature and exposure to natural elements in the environment improve attention, concentration, and cognitive function.	Lower blood pressure: Being in environments with biophilic design elements has been associated with lower blood pressure levels, promoting cardiovascular health.
Increased creativity: Biophilic design stimulates creativity and enhances cognitive flexibility, supporting innovation and problem-solving.	Improved sleep quality: Exposure to natural light and outdoor views helps regulate circadian rhythms, leading to better sleep quality and overall sleep-wake patterns.
Improved mental well-being: Biophilic design elements contribute to a sense of connection with nature, fostering a positive mental outlook and overall psychological well-being.	Faster healing: Studies have shown that exposure to natural elements in healthcare environments can promote faster recovery rates and reduce the length of hospital stays.

by nature, including emotional, social, cognitive, and spiritual dimensions. Results indicated that biophilic design improved individual patient recovery time and treatment efficiency and promoted overall health and well-being. Thus, the physical health benefits of biophilic design have been well-documented in several studies in various fields adjacent to the work environment and confirm a

positive correlation between the two variables (Gillis & Gatersleben, 2015; Kellert & Calabrese, 2015; Ryan *et al.*, 2014; Ryan & Browning, 2020; Zhong *et al.*, 2022).

The mental health benefits have also been investigated. For instance, Park *et al.* (2020) aimed to evaluate the effectiveness of a sensory well-being hub designed to cater to the needs of diverse learners with developmental disabilities and distinct sensory profiles. The study took place at a public high school in Chicago. The site was a freestanding structure equipped with a range of sensory features aim at supporting individuals with a wide range of atypical sensory processing, particularly those who are neurodiverse. The results showed that the sensory well-being hub was utilized for both scheduled and unscheduled visits. Among the various elements within the hub, the most frequently visited ones included a beanbag accompanied by a weighted blanket, a sensory cocoon featuring tensile fabric and a media wall, and a fidget wall incorporating multiple components. Students diagnosed with autism spectrum condition exhibited different patterns of sensory intervention usage compared to those without such a diagnosis, despite having similar sensory profiles. These findings have significant implications for the design of other neuroinclusive environments in both educational and occupational settings. Therefore, physical and mental health benefits can be seen with the use of biophilic design, including the following for consideration in industry and office environments.

2.1. Life expectancy

According to a study conducted by the German Institute of Global and Area Studies, there is a significant correlation between working in offices equipped with high-level filtration systems and increased life expectancy (Patterson, 2017). The study discovered that employees in Tishman's China offices were estimated to gain an average of 6.3 days per year in life expectancy compared to their counterparts working in unfiltered workplaces. This study emphasizes the importance of integrating high-quality filtration systems in office environments to promote employee well-being and longevity. In addition, air quality in the workplace can impact cognitive performance, productivity, and overall job satisfaction (Fisk *et al.*, 2011). Therefore, investing in air filtration systems can not only benefit the health of employees but also contribute to a more productive and satisfied workforce. It is recommended that office managers prioritize air quality when designing work environments and invest in high-quality air filtration systems to ensure employee health and well-being.

2.2. Productivity

According to a study conducted by Cardiff University in Wales in 2014, the incorporation of plants into office

spaces that were previously devoid of greenery increased productivity by 15%. This finding aligns with previous laboratory studies and contradicts modern "lean" management techniques and contemporary economic and political trends. The researchers suggested that incorporating natural elements in the workplace can create a more pleasant and comfortable working environment, leading to more profitable office-based work (Langer, 2021). Therefore, companies should consider integrating biophilic design elements, such as plants and natural lighting, into their office spaces to improve employee well-being and productivity.

2.3. Neurodiverse tendency toward rumination

In 2015, Stanford University conducted a study that demonstrated the psychological benefits of nature for mental health. The study revealed that spending time in natural surroundings, such as walking in a park, can help reduce rumination, which is associated with an increased risk of depression and other mental health disorders. This finding emphasizes the importance of incorporating natural elements and green spaces into urban environments to support mental well-being, especially for neurodiverse individuals who may have a tendency toward rumination (Bratman *et al.*, 2015). Therefore, including natural elements in the design of smart cities can provide a more holistic and inclusive environment that supports the mental health and well-being of all individuals.

2.4. Absenteeism

According to a study by Lerner and Stopka in 2016, various architectural elements, such as view quality, lighting quality, and window area, can significantly impact employee absenteeism. When these factors were considered together, they accounted for up to 10% of the variation in sick leave days taken. This highlights the crucial role of the incorporation of biophilic design principles in creating office environments that support employee health and well-being. By incorporating natural elements such as daylight, outdoor views, and greenery, workplaces can not only promote physical health but also enhance employee satisfaction and productivity, ultimately reducing absenteeism rates. Therefore, integrating biophilic design principles in office spaces can lead to a more productive and sustainable work environment.

2.5. Eye fatigue

Extended use of digital screens can cause visual fatigue, a condition that can be alleviated by regular exposure to visual green spaces, as suggested by a study conducted by Zari (2017). Therefore, incorporating biophilic design elements such as plants and natural light into office

environments can offer employees a break from prolonged screen time, contributing to their overall well-being and comfort. Moreover, research has shown that biophilic design can also improve air quality, reduce stress, and enhance productivity, which ultimately translates to improved business outcomes. Therefore, integrating biophilic design principles into office environments can offer a range of benefits, including reduced employee absenteeism, higher job satisfaction, and increased overall productivity.

To address eye fatigue, it is important to consider the visual breaks and relief that nature can provide. One way to achieve this is by incorporating distant views into the design of window views. Research on the evaluation of landscape distance seen in window views on visual satisfaction has shown that views with a balance of nearby and distant content tend to be more beneficial in relieving eyestrain (Kent & Schiavon, 2022). By incorporating natural elements in the distant views, such as landscapes, greenery, or natural scenery, occupants can shift their focus from close-up tasks to the visually soothing elements in the distance. This allows the eyes to relax and reduces the strain caused by prolonged visual exposure to nearby content. Designers can utilize this knowledge to create window views that provide a visually satisfying experience and contribute to the overall well-being and comfort of the occupants.

3. Benefits of biophilic design: Enhancing well-being and performance

The incorporation of nature into built environments has been found to have a positive impact on human well-being and performance (Frumkin & Fox, 2011). This has been supported by two prominent theories: Attention Restoration Theory and Stress Recovery Theory. Attention Restoration Theory proposes that exposure to natural environments can help restore cognitive function and attention. On the other hand, Stress Recovery Theory suggests that natural environments can help individuals recover from stress by reducing negative emotions, heart rate, blood pressure, and stress-related hormones such as cortisol. Understanding these theories is significant for this study as they provide a framework for the importance of incorporating natural elements into the built environment to improve well-being and performance (Jiang *et al.*, 2021).

3.1. Psychological and physiological responses

Both the psychological effects and physiological responses of humans to biophilic design speak to the benefits of adopting it as a strategy for both employee productivity and well-being and support arguments for sustainability in

smart cities. For instance, exposure to natural environments has been linked to improved adaptability, alertness, attention, concentration, and emotion regulation. Studies have reported that engaging with natural environments offers enhanced emotional restoration compared to urban environments that lack natural elements. These natural environments have been found to be associated with reduced instances of tension, anxiety, anger, fatigue, confusion, and overall mood disturbance (Beute & de Kort, 2014; Tang *et al.*, 2022; Williams *et al.*, 2018). Physiological responses to connections with nature include muscle relaxation, lowered diastolic blood pressure, and reduced cortisol levels in the bloodstream (Dusek & Benson, 2009; Knight & Rickard, 2001). Improved indoor air quality through the use of plants and high-level air filtration systems has been linked to increased life expectancy and cognitive abilities while decreasing the prevalence of sick building syndrome (Chen *et al.*, 2017; Wood *et al.*, 2002). Incorporating biophilic design elements into the workplace has been associated with a range of mental and physical health benefits (Table 3). Studies have shown that workplaces with natural elements can lead to a 15% higher level of well-being, a 6% higher level of productivity, and a 15% higher level of creativity. Exposure to nature has also been linked to reduced negative emotions and stress, as it helps decrease self-reported rumination, which is often associated with depression and other mental health disorders. In addition, spending time in natural environments has been found to enhance cognitive functioning, improving working memory and overall cognitive performance. Furthermore, offices with plants have been shown to increase employee engagement, productivity, and well-being, leading to better staff retention and attracting top talent. The presence of plants also offers health benefits by reducing bacterial colonies by 60%, decreasing headaches by 24%, and reducing eye irritation by 52%. These findings underscore

Table 3. Benefits of biophilic design supported by corresponding statistics

Benefits	Statistics
Improved well-being and productivity	15% higher well-being, 6% higher productivity, 15% higher creativity
Reduced negative emotions and stress	Decreased self-reported rumination
Enhanced cognitive functioning	Improved working memory and cognitive performance
Improved employee engagement and retention	Increased employee engagement, productivity, and well-being
Health benefits	Reduced bacterial colonies by 60%, decreased headaches by 24%, reduced eye irritation by 52%

the significant impact of incorporating biophilic design in the workplace, promoting both the mental and physical well-being of employees.

Given that biophilic design is rooted in the understanding that humans have an innate desire for connection with nature, incorporating nature into the built environment can improve psychological and physiological functioning, ultimately enhancing well-being, productivity, and performance. As such, these and other studies highlight the substantial benefits of implementing biophilic designs in office environments. By incorporating multisensory connections with nature through architectural and interior concepts, biophilic design seeks to improve the physical, emotional, and cognitive well-being of individuals in dense urban settings. In addition to the benefits mentioned, biophilic design can also promote sustainability in smart cities. Integrating natural elements into the built environment can reduce the carbon footprint of buildings by increasing energy efficiency through the use of natural lighting, ventilation, and passive heating and cooling techniques. Green roofs and living walls can also help reduce urban heat island effects, provide insulation, and improve air quality. These benefits contribute to the creation of sustainable urban environments that prioritize the well-being of inhabitants.

Research from various institutions, including the Harvard Center for Health and the Global Environment, the American Psychological Association, and the University of Exeter, consistently demonstrates the positive impact of biophilic design on cognitive functions, disease symptoms, quality of life, employee engagement, productivity, and motivation (Browning & Ryan, 2020; Depledge *et al.*, 2011; Van den Bosch & Bird, 2018). Furthermore, a 2010 study by the University of British Columbia investigated the stress-reducing effects of wood and plants in an office environment, while a 2-year study from the Plants and Indoor Environmental Quality Research Group at the University of Technology Sydney found that green walls could reduce CO₂ levels and improve productivity by reducing headaches and lethargy among workers (Fell, 2010; Fleck *et al.*, 2020). Another study from the University of Queensland's School of Psychology concluded that offices enriched with plants could boost productivity by 15% (Nieuwenhuis *et al.*, 2014). Overall, the scholarship supports the significant benefits of biophilic design in workplace settings. By integrating elements of nature into the built environment, organizations can enhance employee well-being, productivity, creativity, and motivation, ultimately improving the overall workplace experience and fostering positive relationships among colleagues.

4. Recommendations

With the growing inorganic urban world, biophilic design has emerged as an essential element in creating spaces that promote well-being, reduce stress, and enhance productivity (Zhong *et al.*, 2022). By incorporating elements of deep nature and multisensory immersion, biophilic design has been shown to significantly increase positive feelings compared to typical urban environments (Aristizabal *et al.*, 2021). This approach to design not only appeals to our visual and tactile senses, such as through oval atriums with native trees and mesh walls but also positively impacts our physiological responses. Moreover, studies have shown that forest environments can increase parasympathetic nervous system activity, which helps restore a sense of calm and safety while suppressing sympathetic activity associated with stress responses (Lee *et al.*, 2011). By integrating natural elements into our surroundings, we can decrease nervous energy and lower cortisol levels, improving overall well-being (Beute & de Kort, 2014). Interestingly, research suggests that the immune-boosting effects of nature immersion may differ between genders, with men experiencing increased immune function for up to 30 days after a forest walk, while women show improvements for only 7 days (Antonelli *et al.*, 2022). The finding implies that workplace interventions targeting female populations may need to prioritize indoor nature experiences or facilitate more extended outdoor nature experiences. The following section will first introduce industry examples of biophilic design that demonstrate the measurable impact of connecting with nature and promoting multisensory immersion in our daily environments, followed by more specific elements that comprise them.

4.1. Industry examples

Amazon is nearing completion of plans for PenPlace, the next phase of its HQ2 in Arlington, Virginia. While the project was just put on hold, it focuses on sustainability, with HQ2 operations powered by 100% renewable energy from a combination of off-site and on-site solar projects (Day, 2023). PenPlace will provide more than 100,000 sq ft of retail space, multimodal pathways, and over 2.75 acres of public park space. The development aims to prioritize access by foot, bike, and public transportation, while also providing an open-air amphitheater and dog run for the community. Amazon has committed to leadership in energy and environmental design Platinum certification, low-flow fixtures, and bird-safe glass, among other sustainable design elements. Over 26,500 sq ft of space will be dedicated to Arlington County Community High School, and the Helix, a spiral-shaped building, will offer meeting spaces, living walls, and an artist-in-residence program.

In addition to the PenPlace development in Arlington, Amazon has undertaken other innovative projects, such as the futuristic biospheres in Seattle (Bishop, 2016). These spheres resemble parks more than offices, featuring over 3,000 plants from 30 countries, tree-house meeting rooms, water features, a birdcage-themed conference room, environmental fogging, and a five-story living wall. These examples build on previous examples of water features in various businesses (Figure 3). Amazon encourages walking meetings within the spheres, promoting employee well-being and engagement with nature.

Similar to the PenPlace project, the Seattle biospheres also contribute 2.75 acres of public park space for community use, including immersive forest rooms. This demonstrates Amazon's commitment to creating shared spaces that benefit both employees and the local community. Furthermore, Amazon has pledged to power 100% of its HQ2 operations with renewable energy through a mix of off-site and on-site solar projects. This aligns with the company's Climate Pledge, which aims for net-zero carbon emissions across all Amazon operations by 2040. By incorporating renewable energy and sustainable design elements in its projects, Amazon sets an example for other corporations to prioritize sustainability and environmental responsibility.

Lendlease's new global headquarters in Australia features the country's first breathing green wall, which lifts the biophilic office design to another level (Jackson & Mansfield, 2019). This innovative wall, created by Junglefy, incorporates around 5,000 plants and serves as an active, modular green wall system. Scientifically proven to remove air pollutants such as carbon dioxide and volatile organic compounds more effectively than other plant-based systems, the breathing wall offers numerous benefits.

In addition to improving air quality, the breathing wall also acts as a natural cooling system, reducing the

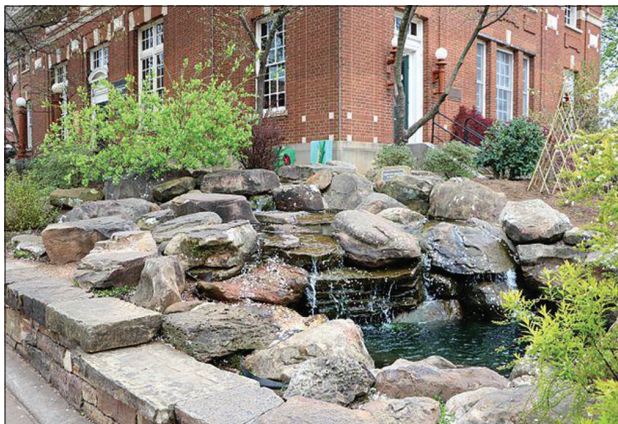


Figure 3. Old post office waterfall, fayetteville historic, 2016.

surrounding air temperature and leading to increased energy efficiency and lower air conditioning costs. Moreover, the wall serves as a sound barrier, enhancing the office's acoustics and providing a more comfortable working environment. The breathing wall comprises modules made from linear, low-density polyethylene, which can be infinitely recycled. The modules are filled with a coconut fiber-rich growing medium. To ensure uniform airflow across the plants and growing medium, an electric axial impeller is employed, enhancing the absorption of carbon dioxide and maximizing the amount of air that can be filtered and cooled by each module.

By incorporating biophilic elements such as the breathing green wall, Lendlease headquarters showcases how office spaces can be designed to promote both environmental sustainability and employee well-being. This innovative approach to office design serves as an inspiration for businesses worldwide to adopt biophilic design principles in their workspaces.

5. Biophilic design elements

This section will explore the interconnectedness of biophilic design elements with spacemaking, wayfinding, and soundscapes, highlighting their collective impact on creating environments that promote well-being and enhance the user experience. Biophilic design, with its emphasis on integrating natural elements and patterns into built environments, serves as the foundation for creating spaces that mimic the restorative qualities of nature. By incorporating elements such as plants, natural light, and organic shapes, spacemaking techniques enhance the overall aesthetic appeal and functionality of the environment. Wayfinding strategies play a vital role in guiding individuals through the space, ensuring ease of navigation and a sense of orientation. By integrating natural wayfinding cues, such as the use of colors, patterns, and materials inspired by nature, individuals can intuitively understand their surroundings and establish a stronger connection with the built environment. In addition, soundscapes, encompassing the acoustic qualities and auditory stimuli within a space, contribute to the overall sensory experience. By incorporating natural sounds and minimizing disruptive noises, biophilic design can create a harmonious and calming auditory environment. Understanding the relationships between these key components allows for the thoughtful integration of biophilic design principles in the creation of spaces that not only promote well-being but also inspire a deeper connection with the natural world.

5.1. Spacemaking

Spacemaking with biophilic design involves creating environments that provide a sense of refuge and

relaxation, allowing individuals to readjust their sensory and social control over their surroundings. Biophilic design concepts such as prospect and refuge, enticement and peril, and sensory gardens are all used to create spaces that promote relaxation and reduce stress (Tekin *et al.*, 2023). The use of green spaces as a primary recalibration zone is a common approach in biophilic design. Access to green spaces from common areas, such as a courtyard or rooftop garden, can provide a sense of relaxation and rejuvenation for occupants (Parsaee *et al.*, 2019). Sensory gardens, which may include edible plants and herbs, can also provide a calming effect and offer an opportunity for tea-making or other sensory experiences (Wilkinson & Orr, 2017).

When it comes to the output of oxygen, trees are more effective than plants. Trees produce more oxygen and have a greater impact on the overall air quality in a space. In addition to using natural elements such as plants and trees, using boundaries and nooks can also create a sense of safety and privacy within a space (Sieghardt *et al.*, 2005). For example, trees can act as boundaries that divide up zones of space within an atrium instead of using walls. Overall, spacemaking with biophilic design is about creating environments that promote relaxation, rejuvenation, and a connection with nature. Whether through the use of green spaces, sensory gardens, or natural boundaries, the biophilic design aims to create spaces that promote emotional and mental well-being.

5.2. Wayfinding

Navigating through spaces that incorporate natural elements can be a complex task, and biophilic design recognizes that effective wayfinding is essential to maximize the benefits of such spaces. By providing clear visual cues and intuitive paths, wayfinding can help individuals navigate and understand their surroundings, contributing to an overall positive experience. Effective wayfinding not only improves the usability and accessibility of spaces but also promotes social interaction and gatherings, leading to increased personal relationships among individuals within the space.

However, it is important to recognize that some individuals may find certain features of biophilic design overwhelming or distracting. As such, it is essential to provide countermeasures that can accommodate the diverse needs of users, including neurodiverse individuals, to ensure that everyone can enjoy the benefits of biophilic design. A study by Fidan *et al.* (2021) emphasizes the need for balance in biophilic design by recognizing the importance of providing supportive measures for those who may find certain aspects challenging. For example,

sensory gardens or quiet spaces can provide a respite for individuals overwhelmed by the visual and auditory stimuli of biophilic spaces. Overall, effective wayfinding and thoughtful design that accommodates diverse needs are crucial elements of successful biophilic design, enabling individuals to reap the benefits of interacting with nature in built environments.

Effective wayfinding design is a critical component of biophilic design, as it facilitates navigation and comprehension of one's surroundings. Design elements such as curved edges that gradually reveal can be more effective than sharp corners in guiding individuals through a space. In addition, carpets with patterned ways and colored zones can help direct visitors toward safety and desired areas. To be successful, wayfinding design should be intuitive and nonverbal, allowing individuals to quickly understand where they are and how to get where they want to go (Jiang & Verderber, 2017). It is also necessary for companies to develop mapping systems to assist individuals in knowing where they are and where they should be in the physical space. Intensification of signage and visual communication can aid in wayfinding, and strategic use of color, lighting levels, signage, and art can act as landmarks to assist our brains in innovating a positioning system. These design elements are particularly important for the neurodiverse population, who thrive on repetition, predictability, and clear boundaries to feel "safe" and "in control" (Crawford & Wu, 2011).

Movement is a significant element of biophilic design and can be accomplished by incorporating subtle changes in air temperature, airflow, and surface temperatures, which can provide a calming effect by simulating a natural environment. The use of thermal zones, similar to those found in butterfly houses, can also create a shifting sensory experience for individuals. This approach has been supported by research, such as a study by Ryan and Browning (2020), which emphasizes the importance of movement in biophilic design. By integrating natural movements into the built environment, organizations can further enhance employee well-being, productivity, creativity, and motivation, ultimately improving the overall workplace experience.

5.3. Natural design

Incorporating natural design elements into a space can significantly enhance the biophilic experience. Materials and elements from nature, when used in their raw or minimally processed state, can reflect the local ecology or geology and create a distinct sense of place (Beatley, 2011). For instance, using local timber and xeriscaping, which involves using native, drought-tolerant plants to

create landscape designs that resemble the climate of the surrounding landscape, can be effective strategies for designing a resilient, biophilic experience (Ryan & Browning, 2020). The use of natural materials, such as wood, stone, and exposed brick, can create a tactile connection with nature. Wood, in particular, has been shown to improve air quality by moderating humidity and creating a link to nature that elicits feelings of warmth, comfort, and relaxation (Alapieti *et al.*, 2020). However, the use of smooth and easily washable surfaces instead of porous surfaces that can retain microbes is necessary and has come under increased consideration during the COVID-19 pandemic (Seidi *et al.*, 2021).

In addition to materials, aesthetic details such as texture, color, sequencing, compartmentalization, temperature, and smells can also contribute to over- or under-stimulation. Textures that mimic bark, scales, or other natural patterns can serve a fidget function on furniture. For instance, using a sequin pillow trend or soft fur-like materials can enhance the tactile experience of space (Badgett, 2020). Natural patterns, such as the iridescence of a hummingbird or the patterning of a bee's honeycomb, can also be used to evoke a connection with nature. Overall, natural design elements and materials can significantly enhance the biophilic experience, creating a sense of place and tactile connection with the natural world.

5.4. Natural lighting

Lighting design is an essential element of biophilic design, and it involves more than just providing illumination. Overhead fluorescent lighting can be overwhelming, and designers need to consider the quality and color of light waves to create a comfortable and stimulating environment. Natural light is an excellent lighting source and is especially beneficial for learning environments. High-placed windows allow natural light to penetrate the space while limiting distractions caused by views. Natural light exposure plays a crucial role in maintaining the optimal balance of serotonin, a hormone associated with mood regulation, while also suppressing the production of melatonin, a hormone involved in sleep regulation (Marchi, 2013).

Light therapy is also an essential aspect of biophilic design. It involves exposing the retina to specific light wavelengths to address imbalances in the circadian rhythm, which denotes the daily hormonal cycle activity observed in many living organisms. This balance is partially influenced by the changing color of daylight throughout the day, with morning light appearing yellow, shifting to a bluer color at midday and transitioning to a reddish tone in the late afternoon. Exposure to natural light helps maintain the equilibrium of serotonin and melatonin. When there

is an imbalance between serotonin and melatonin, our sleep-wake patterns are disrupted, subsequently inhibiting the proper functioning of our neurological and immune systems (Parsaee *et al.*, 2019).

Lighting design can also incorporate an element of fire through UV lighting and heat therapy. Light exposure holds significant implications for the production of serotonin, often referred to as the "happy hormone". Serotonergic neurons play a crucial role in regulating brain development and function, and disruption in these neurons has been linked to various psychiatric disorders, including depression and anxiety. Thus, proper lighting design can have a significant impact on mood, sleep, and overall health (Bhardwaj, 2021).

5.5. Soundscapes

Soundscapes play a significant role in biophilic design, as they have the potential to impact our physical and emotional well-being. The use of nature and calming sounds can counteract hormones released by the body when under stress or pain, such as endorphins. Ambient nature sound installations can improve three core neuroinclusive design goals: focus, stimulation, and relaxation (Chanda & Levitin, 2013). This is particularly important for those who are neurodivergent and either hypersensitive to sound or seeking opportunities for multiple sound activations (Harder, 2022). The sounds of nature, such as rivers and rain, are popular choices for creating a calming and relaxing environment (Chu *et al.*, 2009).

In modern workplaces, noise pollution is a common issue, which can lead to sensory sensitivity and distraction. To combat this, spaces can be designed effectively to absorb sound through partition systems or with acoustic baffling to create the illusion of private space. Research shows that exposure to nature sounds, compared to urban or office noise, accelerates physiological and psychological restoration up to 37% faster after a psychological stressor, reduces cognitive fatigue and increases motivation (Erfanian *et al.*, 2019; Ulrich *et al.*, 1991). Another interesting aspect of soundscapes is the use of bird noises as directional markers. By incorporating directional sound cues, people can navigate spaces more easily and intuitively, creating a more natural and intuitive wayfinding experience (Jonsson, 2002). These considerations demonstrate that soundscapes are an important element in biophilic design as they can help create a calming and restorative environment that promotes well-being and productivity.

5.6. Digital and bioart

Digital and bio art can be used to bring biophilic design into the digital realm, further enhancing the experience of

nature within indoor spaces. One example of digital art is a digital waterfall wall that can be programmed to mimic local weather patterns, providing insight to those working in basement areas without windows and for individuals who dislike unexpected weather changes (Fox, 2016). Simulated aquariums can also be used to teach about endangered marine life and ecosystems (Lachenmyer & Akasha, 2022). Natural analogs, which are materials and patterns that evoke nature, can also be used as a biophilic design element. Examples of natural analogs include building elements that resemble shells and leaves, furniture with organic shapes, and visible wood grain. While they may not have the same impact as dynamic types of nature, artworks and murals depicting scenes from nature have been proven to reduce anxiety and discomfort. The act of viewing natural scenes stimulates a larger portion of the visual cortex compared to non-nature scenes, triggering an increased activation of pleasure receptors in our brain and facilitating faster recovery from stress (Tharim *et al.*, 2022).

Bioart, which uses nature as an artistic medium, can also be incorporated into biophilic design. Artwork that helps filter air quality, such as moss walls, can be used to purify indoor air (Moslehian *et al.*, 2023). Other examples include lanterns with filtered air and living façades that support bird and insect habitats (De Wilde & de Souza, 2022). In addition to digital and bioart, plants can also be used to enhance the biophilic experience. Certain plants, such as the bamboo palm and pothos, have been shown to aid in the removal of harmful elements such as benzene and formaldehyde from indoor air. Plant names can also be displayed to educate individuals on the types of plants used in the space (Peng *et al.*, 2022). Incorporating bird feeders, butterfly gardens, and koi ponds can also help bring nature into the indoor environment. Thus, incorporating elements of digital and bioart, natural analogs, and plants can help create a more immersive biophilic experience in indoor spaces.

5.7. Extended reality (XR), artificial intelligence (AI), and biophilia

XR and AI offer promising tools for assisting neurodiverse populations in the workplace (Hutson, 2022). These technologies can provide personalized and adaptive support for individuals with unique needs, allowing them to better acclimate to a new work environment and manage their stress levels. Virtual reality (VR), in particular, has been studied extensively for its mental health benefits, including reducing anxiety and improving self-regulation (Wang *et al.*, 2022). VR simulations can help individuals practice and prepare for real-life workplace scenarios, allowing them to feel more comfortable and confident when faced with similar situations in the future (Birkheim

et al., 2023). Moreover, VR has been widely used in architectural studies to simulate and manipulate important parameters that are crucial for evaluating design elements and their impact on occupants. In these studies, VR serves as a tool to modify variables such as window size, daylight, and spatial arrangements, enabling researchers to assess the effects of these factors on occupant satisfaction and well-being (Banaei *et al.*, 2020). While VR has been shown to have potential mental health benefits, it is important to clarify that its primary purpose in architectural research is not solely focused on mental health but rather on providing a controlled environment for investigating design parameters. By utilizing VR technology, researchers can gain valuable insights into the effects of different design choices on occupant experiences, allowing for informed decision-making and the creation of more user-centered and biophilic design solutions.

AI-powered tools can also provide valuable support for neurodiverse individuals in the workplace. For example, AI chatbots can provide personalized coaching and support, helping individuals manage stress, regulate their emotions, and stay on task (Luo *et al.*, 2022). In addition, AI-powered sensory systems can adjust real-time lighting, temperature, and sound levels to create a more comfortable and calming work environment (Patel *et al.*, 2022). By combining biophilic design with XR and AI technologies, employers can create a workplace environment that is not only visually pleasing but also supportive and accommodating for neurodiverse individuals. The combination can lead to improved job satisfaction, productivity, and overall well-being for employees while also benefiting employers through reduced turnover rates and increased job performance.

To effectively implement biophilic design principles in workplace environments, it is crucial to consider the following key recommendations (Table 4). First, organizations should prioritize the integration of natural elements, such as plants, natural light, and views of nature, to create a visually appealing and soothing atmosphere. Second, attention should be given to the selection of materials that mimic natural textures and patterns, fostering a sense of connection with the natural world. Thirdly, incorporating elements of nature in communal areas and gathering spaces can promote social interactions, collaboration, and a sense of community among employees. In addition, providing opportunities for physical movement and access to outdoor spaces can further enhance the benefits of biophilic design. Finally, it is essential to ensure that the design accommodates the diverse needs of all employees, including those who are neurodiverse, by considering factors such as acoustics,

Table 4. Recommendations for incorporating biophilic design

Recommendation	Description
Integrate natural elements	Incorporate natural elements such as plants, water features, and natural materials like wood and stone to create a connection with nature and evoke positive emotional responses.
Maximize natural light	Use abundant windows, skylights, and light wells to enhance visual comfort, support circadian rhythms, and create a connection with the outdoor environment.
Provide access to views	Incorporate views of vegetation, landscapes, or water bodies to promote relaxation, stress reduction, and cognitive restoration.
Incorporate biomorphic elements	Utilize organic shapes and fractal patterns to mimic elements found in nature, increasing visual interest and evoking positive emotional responses.
Use natural materials	Incorporate natural materials like wood, stone, and natural fibers in building construction and interior finishes to create a welcoming and harmonious environment.
Integrate living systems	Include indoor plants to improve air quality, enhance well-being, and foster a sense of connection with nature.
Incorporate water features	Incorporate water elements such as fountains or water walls to provide sensory stimuli, promote relaxation, and create a tranquil atmosphere.
Optimize thermal factors	Create conditions mirroring natural environments with varying temperatures and airflow to support occupant comfort and well-being.
Incorporate soundscapes	Utilize natural sounds like flowing water or birdsong to create a soothing and calming environment while masking unwanted noise.

lighting, and spatial layouts. By implementing these recommendations, organizations can create workspaces that not only promote well-being and productivity but also foster a deeper connection with nature, resulting in a more sustainable and harmonious work environment.

6. Conclusion

Humans have coexisted and evolved in harmony with nature and its systems. As a result, human minds and bodies operate more effectively when surrounded by natural elements. Biophilic design serves as an ideal collaborative tool for promoting productivity, reducing healing time, enhancing learning capabilities, and fostering community cohesion. It offers a perfect partnering mechanism for business vendors, hospital owners, school administrators, contractors, and city planners alike who are seeking to reap maximal value through development and design.

One particularly important benefit of biophilic design is its potential to support the needs of neurodiverse

populations. For those with sensory processing disorders, access to green spaces or sensory gardens can be a crucial recalibration zone, allowing individuals to readjust their sensory and social control over their environment. In addition, a clear wayfinding design that is intuitive and nonverbal can be especially helpful for those with autism spectrum disorder or attention-deficit hyperactivity disorder. Using natural materials and elements that reflect the local ecology can also create a distinct sense of place and help neurodiverse individuals feel more comfortable and secure in their surroundings.

Biophilia offers a wide range of economic advantages across multiple sectors. The available evidence suggests that incorporating biophilic elements into the workplace, such as nature-inspired designs, has a positive impact on staff productivity. This, in turn, leads to economic benefits that can range from US\$1,000 per employee to as much as US\$3.6 million company-wide (Kropman *et al.*, 2022). Within the healthcare sector, which represents a US\$2.5 trillion industry, even the simple act of providing hospital patients with natural views from hospital beds could result in over US\$93 million in annual savings nationwide, as recovery time required for patients following major surgeries is shortened significantly (Koppel, 2022). Recent research from neuroscience and endocrinology shows the crucial role that experiencing nature has for our physiological well-being (Coria-Avila *et al.*, 2022). Implementing biophilic design into workplaces, healthcare systems, educational environments, and communities is not just a nice amenity. The strategy has profound economic benefits and can provide a supportive and beneficial environment for individuals with neurodiverse needs and supports sustainability through smart cities with urban design. Therefore, bringing nature into our built environments and design spaces is imperative as it promotes well-being and productivity for all.

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