Linking spatial characteristics of urban green space and mental well-being: green space biodiversity and landscape spatial patterns

by

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B.S., Pusan National University, 2013
MLA, Seoul National University, 2018

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Landscape Architecture and Regional & Community Planning,
College of Architecture, Planning and Design

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2022

Abstract

During the past several decades, much progress has been made in the understanding of how urban green space promotes the mental well-being of urban residents. In particular, the last two decades have witnessed a growing interest in the association between the quantity of urban green space and the effect on residents' well-being. However, little research has attempted to disentangle the linkage between the structure of urban green space and mental well-being beyond the quantity aspect. To address this question, this dissertation includes a literature review regarding restorative mechanisms influenced by the spatial characteristics of urban green space. Also, this dissertation includes experimental and observational studies: a biodiversity study and a landscape pattern study.

In the biodiversity study, I examined how the biodiversity of campus green space can promote mental well-being of college students by assessing their visual and auditory perceptions of two green spaces having either low or high biodiversity. I employed a 2 by 2 study design, in which 319 students were randomly assigned to one of four treatments: (1) low biodiversity without sound, (2) high biodiversity without sound, (3) low biodiversity with sound, and (4) high biodiversity with sound. In a controlled setting, students viewed on a computer a 360-degree-view video of either a low- or high-diversity site, with or without the natural sounds at each site, that had been recorded on the Kansas State University campus (a grassy lawn area, and a native meadow garden). The restorative status and mood of students were evaluated both pre-intervention and post-intervention via a self-reported survey. The results of this study revealed that neither biodiversity level nor sound by themselves had any significant effect on the mood or restorative status of these college students. However, a significant interaction effect between the

visual and auditory perceptions was found. Students who were exposed to a high-biodiversity environment with natural sound conditions were shown to have lower levels of negative mood states compared to those without natural sound conditions.

In the landscape-pattern study, I explored how landscape patterns (i.e., composition and configuration) are associated with the mental health of residents in the city of Chicago. This study used mental health and socioeconomic data from a total of 6,405 residents from 61 Chicago communities in the Healthy Chicago Survey conducted by the Chicago Department of Public Health. High-Resolution Land Cover (HRLC) data were used to calculate urban green space (e.g., trees, grass, and water). Landscape metrics were quantified to measure landscape patterns, including percentage, size, distance, and aggregation of urban green space in 61 community areas across Chicago. The results of this study showed that residents who resided in urban landscapes with small water bodies and that had greater distances between forested areas (owing to the presence of several large urban parks and forests within the Chicago study area) reported less psychological distress. As for total urban green space, there was a lower level of psychological distress in landscapes with a disaggregated distribution of urban green spaces (i.e., multiple small green spaces) in comparison with a single (or a few) large green space(s).

These two studies have implications for landscape design and planning to improve the mental well-being of urban residents. Using both experimental and observational studies, this dissertation is able to contribute to a better understanding of mental restoration mechanisms provided by green spaces within urban environments on both a micro (site-based) and macro (landscape) scale. Furthermore, the study can provide insights into how landscape patterns and biodiversity affect human well-being in order to find a balance between human use and the conservation of nature.

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Acknowledgments

My first and sincerest appreciation goes to my major professor Prof. Hyung Jin Kim for his consistent support and guidance during my Ph.D. journey. Without his help and support, all of my achievements during my Ph.D. years would not have been possible. He always helps me stand alone as an independent researcher who can conduct scientific studies in environmental design and planning. I also would like to thank all of my dissertation committee members: Prof. Kimberly With, Prof. Sara Hadavi, and Prof. Jin Lee. Sincere gratitude is extended for their countless time spent on advice, guidance, constructive feedback, and consistent support for my dissertation, as well as publication.

Also, I extend my thanks to Prof. Anne Beamish, Prof. Katie Kingery-Page, and Prof. Stephanie Rolley in the Department of Landscape Architecture and Regional & Community Planning. Thank you for giving me teaching/funding opportunities and endorsing me for fellowship, grant, and scholarship applications. I am grateful to all of my Ph.D. colleagues and alumni of the College of Architecture at Kansas State University. Their insights and novel ideas always inspire my scholarship in environmental design and planning.

Last but not least, I would like to convey my deepest gratitude to my family for their unconditional support and consistent encouragement. In particular, my parents Drs. Ha and Lee directly and indirectly encouraged me to pursue a career in academia and engage my sense of intellectual curiosity. Thank you to my brother, Jaehong, for the strength you give me and for listening to my concerns whenever I was discouraged.

Dedication

To my parents Drs. Ha and Lee and my brother Jaehong.

Chapter 1 - Introduction

1.1 Background

Maintaining a healthy lifestyle is becoming increasingly important for the global population. Modern society faces many health-related issues, and mental health is especially salient. A recent report by the U.S. Department of Health and Human Services Substance Abuse and Mental Health Services Administration (SAMHSA) indicates an estimated one in five American adults suffered from a mental illness in 2016 (Ahrnsbrak et al., 2017). As a result of the Covid-19 pandemic, additional concerns have been raised about human health (Shigemura et al., 2020). It is important to note that actions taken by the government during the pandemic, such as quarantines, social isolations, and self-isolation, may negatively impact the mental health of the population (Fiorillo and Gorwood, 2020).

Urban green space might have a preventive and restorative effect on these mental health problems. During the past several decades, much progress has been made in developing empirical evidence for the role of urban green space in psychological well-being. Because humans have an innate tendency to create a connection with nature (biophilia), exposure to urban green space plays a pivotal role in improving mental well-being (Kellert, 1995). According to the attention restoration theory (ART) and the stress reduction theory (SRT), urban green spaces can contribute to better psychological status (Kaplan and Kaplan, 1989; Ulrich et al., 1991). ART proposes that exposure to urban green space helps restore people's mental fatigue by achieving four different experiences: being away, extent, fascination, and compatibility. Likewise, the SRT suggests that stress levels can be reduced when people spend time in nature. Many efforts have been made to disentangle the links between urban green spaces and mental well-being (Amicone et al., 2018; Gladwell et al., 2016; Grazuleviciene et al., 2016; Ojala et al., 2018).

There is a growing body of knowledge demonstrating that viewing natural elements and having contact with nature can promote mental restoration. People in a natural environment are more likely to have better psychological health than those who are in an urban environment or who have no access to nature (Kaplan, 2001; Staats et al., 2003; Ulrich, 1981). Also, much progress has been made in investigating the relationship between mental well-being and the amount of urban green space. Indeed, the amount of urban green space in neighborhoods is negatively associated with mental health problems (Jiang et al., 2014; Lee et al., 2014; Nordh et al., 2009). The greater the amount of urban green space a neighborhood has, the better mental health residents are likely to have (Beyer et al., 2014).

Although numerous studies have researched the effects of urban green space quantity on mental well-being, questions remain regarding the impact of varying types and characteristics of urban green space on mental well-being. In urban and peri-urban contexts, not all types of green spaces are identical (e.g., trees, grass, bodies of water). It is still unclear which types of urban green space are most effective for promoting human well-being and how compositional differences within those urban green spaces (e.g., richness, diversity) influence people's well-being. Along with compositional differences, the spatial distribution of urban green space (e.g., size, connectivity, aggregation) – which is also known as landscape configuration – can vary among urban neighborhoods. With the same amount of urban green space, contiguous green space creates a single large urban green space, while fragmented green space contains several smaller urban green spaces. These compositional and configurational differences may impact people's perceptions and behaviors that determine their overall well-being (Chmielewski et al., 2020; Lee et al., 2008; Zhang et al., 2017a).

Furthermore, the compositional and configurational differences in urban green space can determine site-level biodiversity. It is still unclear whether biodiversity has an impact on mental well-being. Growing evidence has emerged that higher levels of biodiversity in the urban green space are related to greater mental well-being (Carrus et al., 2015; Fuller et al., 2007; Sandifer et al., 2015; Southon et al., 2018). Urban green spaces that have high biodiversity can lead to an increased level of soft fascination and the sense of being away, both of which promote involuntary attention restoration (Cook et al., 2019; Kaplan and Kaplan, 1989; Marselle, 2019).

This dissertation investigates the link between the spatial characteristics of urban green space and mental well-being with a focus on two spatial characteristics of urban green space: landscape pattern and biodiversity.

1.2 Structure of the dissertation

A primary goal of this dissertation is to illuminate the link between urban green space and mental well-being. In particular, this dissertation seeks to address how mental well-being is associated with spatial compositions and configurations of urban green space, rather than just the quantitative aspect of urban green space. Chapter 2 provides a literature review that lays the theoretical foundation for the research presented in this dissertation. In this dissertation, spatial characteristics of urban green space are examined through two different research study designs: experimental (Chapter 3) and observational studies (Chapter 4).

Chapter 3 reports on a 2 by 2 pre-post experimental study with college students. This experimental study investigates the causal effects of green space biodiversity on psychological appraisal that leads to mental well-being. Based on the web-based experiment, this study assesses how the level of biodiversity (e.g., high vs. low plant species' richness) through a combination of visual and auditory stimuli can affect psychological responses.

Chapter 4 presents the observational study using city-level health survey data and high-resolution landcover data in the city of Chicago. This chapter explores how landscape composition and configuration are related to the mental health of Chicago residents while controlling for individual-level socioeconomic status.

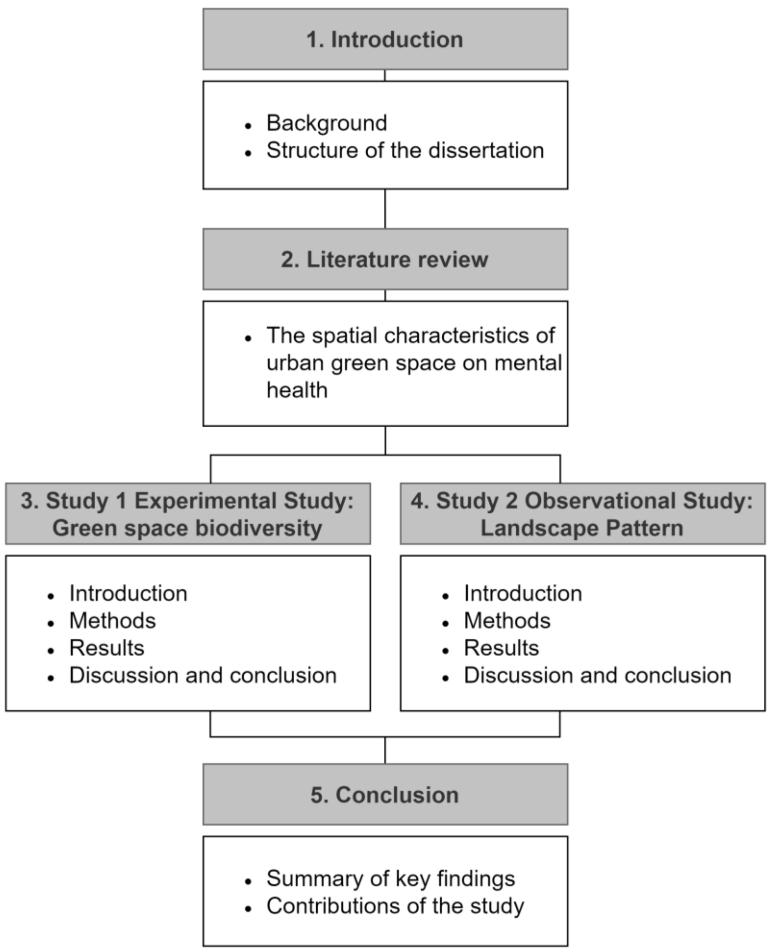

Figure 1 The structure of the dissertation

These two research designs are complementary to each other in examining the role of the spatial characteristics of urban green space on mental well-being. The experimental study examines the causal effect that the spatial composition (biodiversity) of urban green space could have an impact on mental well-being at a local site scale. Through this web-based experiment, the study focuses specifically on how extremes in biodiversity (high vs. low) for one type of green space can affect psychological appraisal, and subsequently lead to an improved mental state. Two different campus environments were used for the experiment: low biodiversity (manicured lawn areas) and high biodiversity (native meadow) settings. Using the integration of visual and auditory stimuli, four different campus environments were tested to examine the mental restoration of college students. This study explores the following research questions that investigate how landscape elements can increase restorative effects for college students:

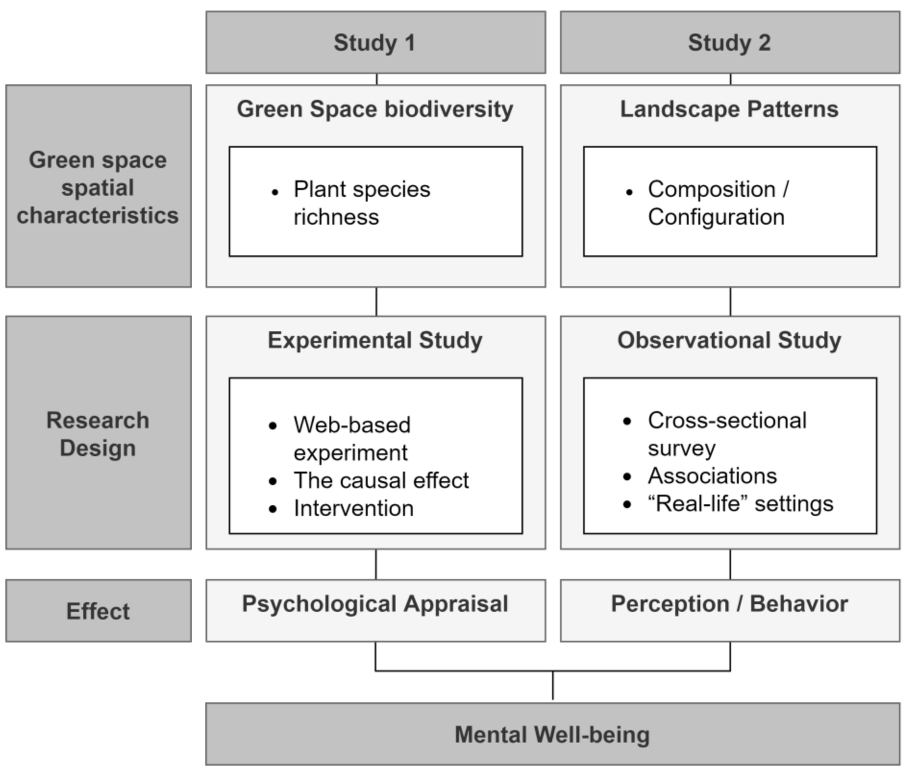

Figure 2 The framework of the two studies

- How can site-level biodiversity in campus green space affect the mental restoration of college students?
- How do the sounds of nature associated with site-level biodiversity in campus green space affect the mental restoration of college students?
- Can the integration of visual and auditory stimuli effectively improve restorative and mood states?

At a broader landscape scale, the second study examines the association between the spatial distribution of urban green space and mental health in a "real-life" setting. Through cross-sectional survey data, this observational study explores how the spatial distribution of urban green space is associated with the mental health of urban dwellers in a major metropolitan city (e.g., Chicago) within the United States. The underlying assumption of the restorative mechanism in this study is that landscape patterns might influence the perception and behavior of people. Landscape metrics were employed to quantify the composition and configuration of urban green space across 61 community areas of Chicago. Psychological distress and socioeconomic status (SES) were derived from the Healthy Chicago Survey (HCS) to explore the association between mental health and landscape patterns. In particular, this study investigated the following research questions that address how landscape patterns are associated with the mental health of Chicago residents:

- Which types of urban green space (e.g., grass, trees, water) have a significant impact on mental health?

- Is the diversity of green-space types within a landscape associated with mental health problems?
- Is the spatial distribution of urban green space (e.g., size, aggregation, connectivity) under each type (e.g., trees, grass, or water) associated with mental health problems?
- Is the amount of total green space (grass, trees, and water combined) related to urban residents' mental health problems?
- How is the spatial distribution of total green space (grass, trees, and water together) associated with mental health problems?

Chapter 2 - Literature review

This literature review examines a wide range of existing literature on the relationship between urban green space and mental well-being. The main purpose of this review is to explore research trajectories and identify which research questions have, so far, been understudied. This literature review mainly focuses on the role of characteristics of urban green space on mental well-being. Discussions are followed to illuminate the mechanism of mental well-being driven by urban green space environments.

Section 2.1 provides a background on the spatial characteristics of urban green space and mental well-being. Section 2.2 discusses methods for filtering articles, including criteria for the inclusion and exclusion of literature. Section 2.3 presents five different categories of urban spatial characteristics previously discussed in the literature: 1) the presence (view) of urban green space, 2) the amount of urban green space, 3) the proximity (accessibility) of urban green space, 4) the types of urban green space, and 5) the structure of urban green space. Finally, section 2.4 explains the pathway for achieving mental well-being driven by the spatial characteristics of urban green space.

2.1 Introduction

In recent decades, a growing body of literature has illuminated the relationship between mental well-being and urban green spaces. In epidemiological studies, people living in neighborhood environments that offer accessible urban green spaces have fewer mental health problems – such as stress, depression, and anxiety – than those without such neighborhood access (Cox et al., 2017; Larson et al., 2018; Mukherjee et al., 2017; Nichani et al., 2017; Pun et al., 2018; Tomita et al., 2017). The provision of urban green space has additional psychological benefits, such as increased life satisfaction, attention restoration, positive mood, social cohesion, and perception of safety (Aziz et al., 2021; Cottagiri et al., 2022; Maas et al., 2009; Park et al., 2011; Ruijsbroek et al., 2017).

The utilization of these psychological benefits from nature is limited by the insufficient provision of urban green infrastructure. Rapid and continued urbanization across the world has significantly reduced urban green space (Chan and Vu, 2017; Zhou and Wang, 2011). Further, the provision of new urban green spaces in high-density cities poses significant challenges due to urban desertification and land scarcity (Choumert and Salanié, 2008; Haaland and van den Bosch, 2015). Thus, it is important to maximize the benefits of existing urban nature through landscape design and planning strategies by analyzing the spatial characteristics of urban green space.

The spatial characteristics of urban green space (e.g., compositional and configurational spatial patterns) are interconnected with human health through multiple reciprocal causes and effects (Yeh et al., 2020). Previous studies have shown a series of pathways through which spatial characteristics of urban green space might affect human perception and behavior: environmental exposure, visual perception, frequency, and duration of visits to urban green space (Brown et al., 2018; Grahn and Stigsdotter, 2010; Neuvonen et al., 2007; van den Berg et al., 2017). These pathways may contribute to the mental health and well-being of urban populations.

The primary goal of this literature review is to identify the spatial characteristics of urban green space from a broad array of existing literature on mental well-being and urban green space studies. In particular, this review focuses on the physical attributes of urban green space that can be objectively measured and assessed. Through this literature review, it is hoped that planners and policymakers can derive suggestions for landscape design and planning that can improve mental well-being.

2.2 Methods

2.2.1 Search and selection criteria

For this literature survey, I searched online-format peer-reviewed literature in databases journals where mental well-being and green space–related studies have primarily been published. I selected two online databases that abstract these journals: SCOPUS and Web of Science. Some epidemiological research articles were obtained from PubMed and Medline. The following keywords were derived from previous literature on green space and mental well-being studies: 'green space,' 'greenness,' 'greenery,' 'forest,' 'trees,' 'landscape,' 'nature,' 'natural environment,' and 'open space.' The mental well-being keywords used were 'mental illness,' 'disorder,' 'mental health,' 'stress,' 'distress,' 'anxiety,' 'depression,' 'mood,' 'psychological well-being,' 'mental well-being,' 'happiness,' 'satisfaction,' 'belonging,' and 'social cohesion.' This review was restricted to the previous 10 years except for important work in the field (in which case the search extended beyond 10 years). Following the completion of the search, the titles and abstracts of all articles were reviewed by me.

This review followed five criteria for the inclusion and exclusion of studies. 1) Outcome variables had to be psychological, physiological, or medical-record variables that represented the mental health and well-being status of research participants (e.g., physiological stress, mental illness, mental well-being, subscription records for mental health treatment). As part of this review, this study did not examine the literature regarding the direct relationship between green space and non-mental health outcomes (e.g., physical health, general health, or mixed outcomes) but did include studies if there was a mediator effect. 2) Only quantitative research was included. Qualitative and mixed-methods studies were excluded. 3) This review excluded non-geographic or non-environment studies (e.g., studies assessing respondents' perceptions of greenness). 4) During the review process, only peer-reviewed journals were examined; theses, dissertations, conference abstracts, and review papers were not considered. 5) This review was limited to English language publications. I independently extracted the data from publications eligible for review. After completion of the publication search, I independently created an Excel spreadsheet with information on: authors; year of publication; green space spatial characteristics; green space exposure (measurement); mental well-being measurement; mental well-being instrument; confounders; study result; study population and size; study design; study setting (intervention); spatial scale; and media of environmental exposure (e.g., image, video, field study).

2.3 Results

2.3.1 The spatial characteristics of urban green space

The presence (view) of urban green space

The last three decades have witnessed a growing interest in the comparative mental restoration effects of urban versus natural settings. Based on the attention restoration theory (ART) and the stress reduction theory (SRT), simply having contact with nature plays a vital role in mental restoration (Kaplan and Kaplan, 1989; Ulrich et al., 1991). Ulrich's research indicates that natural settings facilitate better psychological states than urban environments without nature (Ulrich, 1981). The comparison between urban (e.g., streets, built-up areas, buildings, roadways) and natural settings has been studied in a wide array of spatial contexts, including forests, grassland, vacant lots (Gladwell et al., 2016; Park et al., 2011; South et al., 2015), schoolyards

(Amicone et al., 2018; van Dijk-Wesselius et al., 2018), and urban parks (Aziz et al., 2021; Wang et al., 2016).

The most commonly used experimental settings in testing restorative environments are forests and urban environments. Forest environments promote greater restoration effects in psychological (e.g., emotion, mood, perceived restorativeness) and physiological relaxation (e.g., blood pressure, heart rate, body temperature) than do urban environments (Bielinis et al., 2021; Bielinis et al., 2018; Im et al., 2016; Ojala et al., 2019; Sonntag-Öström et al., 2014; Tsunetsugu et al., 2013; Yu et al., 2018). Shinrin-yoku (forest bathing) promotes physical and psychological well-being by providing five human sense experiences (vision, smell, touch, taste, and hearing) as a result of exposure to a forest environment (Wen et al., 2019). Moreover, urban trees can provide greater thermal comfort in the summer than impermeable surfaces (Jeong et al., 2016; Klemm et al., 2015).

Additional research has explored how having a window view is related to mental well-being. Brief glances of nature through a window can bring micro-restorative benefits, which contribute to cumulative well-being (Gilchrist et al., 2015). Having a view of nature from a window at home provides a higher level of satisfaction and well-being than does the absence of a nature view at home (Elsadek et al., 2020; Kaplan, 2001). In the workplace context, Kaplan (1993) observed higher job satisfaction among employees who had a view of nature through a window. Workers who have a view of a forest through a window are found to be more likely to have lower stress, higher job satisfaction, and better work performance than those who do not have a window with a view of a forest (Lottrup et al., 2015; Sop Shin, 2007). In the educational context, students who have green-landscape window views are found to have lower stress levels, higher levels of recovery from mental fatigue, and better academic performance (Benfield et al., 2015; Li and Sullivan, 2016).

Researchers conducting nature studies have also examined indoor environments, finding that indoor green environments (e.g., those including indoor plants) lead to greater mental well-being (Dijkstra et al., 2008). People who have indoor plants in the workplace tend to have a high attention capacity, while workers who do not have such environmental settings are likely to have a lower attention span and a higher degree of anxiety and tension (Chang and Chen, 2005; Raanaas et al., 2011).

The amount of urban green space

There is growing evidence that a higher level of urban greenness is associated with greater mental health and well-being benefits (e.g., lower levels of stress, depression, anxiety, psychological distress, mood disorders, and mental illness, and greater psychological well-being and positive mood status) (Andrusaityte et al., 2020; Astell-Burt et al., 2013; Beyer et al., 2014; Brown et al., 2018; Nutsford et al., 2013; Roe et al., 2017; Shanahan et al., 2017; Tomita et al., 2017; Van Aart et al., 2018; Wang et al., 2019b; Ward Thompson et al., 2016). Neighborhood or urban greenness is objectively measured by National Land Cover Database, Normalized Difference Vegetation Index (NDVI), Land Cover Database, and tree canopy coverage using 100m, 300m, 500m, and 1km buffers from respondents' homes (Alcock et al., 2014; Andrusaityte et al., 2020; Beyer et al., 2014; Cottagiri et al., 2022; Lohmus et al., 2021; Pun et al., 2018; van den Berg et al., 2017).

Previous research suggests that people who live near abundant green space are more likely to have a lower level of psychological distress (Astell-Burt et al., 2013). In the same vein, more green spaces are advantageous in that they are associated with less psychiatric morbidity, especially from early to middle age (Astell-Burt et al., 2014). This view is supported by Beyer et al. (2014), who asserted that a high amount of green space is related to reduced symptoms of psychological distress, such as depression, anxiety, and stress. Similarly, Van den Berg et al. (2010) found that daily stress and perceived general health were improved by the quantities of green space. In a longitudinal study, Alcock et al. (2014) found that people who relocate to greener areas are likely to have better mental health status than those who do not. However, not all studies have a significant association between the quantities of urban green space and a reduction in mental health problems (Francis et al., 2012; Larson et al., 2018; Nichani et al., 2017). Only a few studies have attempted to conduct natural experiments that explore the relationship between neighborhood greenness and mental well-being, measuring both physiological and psychological responses (Mennis et al., 2018; Roe et al., 2013; Ward Thompson et al., 2012).

The quantity of urban green space is one of the criteria that affect people's mental health by increasing visual exposure, time spent, physical activity, and perception of safety. Jiang et al. (2014) found that the extent of tree-cover density within view led to a reduction in stress level. Stress recovery increased with an increase in tree-cover density from 1.7% to 24%, but no changes in stress recovery were found in the 24% to 34% range, resulting in an inverted u-shaped (Jiang et al., 2014). An increase in the level of greenery within the window view of an apartment can significantly improve mental well-being (Olszewska-Guizzo et al., 2018). Greater visibility of greenery (the streetscape greenery at street level) was associated with a lower rate of emergency room visits for mental illness (Yoo et al., 2022). Perception of safety is also related to the degree of greenness in the neighborhood (Maas et al., 2009; Mouratidis, 2019).

The amount of urban greenness is positively correlated to time spent on visits to green space near a residence, and the duration of time spent in green space is linked to having fewer mental health problems (van den Berg et al., 2017). The level of neighborhood greenness also promotes mental health benefits not only by passively viewing nature but also by increasing physical activity (e.g., gardening) (Lohmus et al., 2021). Indeed, physical activity is a mediator that explains the underlying mechanism of the relationship between the quantity of urban green space and perceived stress (Pun et al., 2018; Zhang et al., 2018).

The proximity (accessibility) of urban green space

A growing body of literature recognizes the importance of proximity to the greenery in maintaining mental health (Gascon et al., 2018). The accessibility of neighborhood greenness is typically measured by calculating the Euclidean distance to the nearest green space using either NDVI or Land Cover Database (Dzhambov et al., 2018; Fan et al., 2011; Herrera et al., 2018; Mukherjee et al., 2017; Nutsford et al., 2013; Yoo et al., 2022).

The results of previous research have shown that a short distance to green space is conducive to better mental health (Coppel and Wüstemann, 2017). Likewise, having a short distance to green space attenuates mood and anxiety disorders in urban areas (Nutsford et al., 2013). Similarly, Sturm and Cohen (2014) found that the distance to a park is significantly related to mental health. The effectiveness of that distance peaks at 400m. Another study has attempted to analyze the association between the distance to green spaces from children's residences and their psychological distress, such as hyperactivity and inattention. The finding was that children who live near green spaces tend to have less psychological distress (Markevych et al., 2014). Taken together, these studies highlight the importance of proximity to green spaces.

Accessibility to green space allows people more opportunities to visit those spaces (greater frequency) (Coombes et al., 2010; Neuvonen et al., 2007). Living in close proximity to neighborhood greenness increases exposure to green spaces and subsequently enhances overall mental health (Sturm and Cohen, 2014). The proximity of urban parks and urban greenness can increase physical activity among young children, who are more likely to walk to and play at a park (Akpinar, 2017; Roemmich et al., 2006).

The types of urban green space

Not all urban green space is the same — types of urban green space vary depending on landcover types (e.g., forest, shrubland, herbaceous, planted/cultivated, wetlands, water) (Wickham et al., 2021), public open spaces (e.g., parks, sporting fields, natural reserves, community gardens), and private open spaces (e.g., backyards, corporate campuses, communal grounds of apartment buildings) (Wolch et al., 2014). It remains unclear which types of green space have the greatest positive effects on mental well-being.

Among the various types of urban green space in terms of landcover (e.g., forest, rangeland, agricultural land, and wetland), residents in areas with more forest cover are less likely to have mental health complaints (Akpinar et al., 2016). In accordance with this study, Astell-Burt and Feng (2019) found that tree canopy is related to fewer incidences of psychological distress. Aerts et al. (2022) also concluded that woodland spaces are most beneficial for decreasing the prevalence of mood disorders.

Little research has attempted to illuminate the role of various types of urban green space on mental well-being in public and private open spaces. Data from one study suggested that different attributes of public open space have an impact on stress levels. Among the various types of public open spaces, parks were shown to have social support that led to an indirect stress-reduction effect (Fan et al., 2011). Wood et al. (2017) also suggested that parks with natural landscapes and green spaces with recreational purposes have positive effects on mental health.

Several experimental studies have also attempted to explore which types of urban green space within view can improve mental well-being. For example, Tang et al. (2017) compared different landscape sites by using functional magnetic resonance imaging (fMRI). The results of the research highlighted that landscapes containing elements of water and mountains have the greatest restorative value among urban areas, mountains, forests, and water (Tang et al., 2017). In accordance with this study, Deng et al. (2020a) found that higher levels of physiological and psychological well-being were associated with mountain landscapes compared with lake and lawn landscapes. A pine forest was most effective at improving mood and restoration, compared with landscapes with farmed fields or tree-lined urban neighborhoods (Brancato et al., 2022). However, the evidence of such research is equivocal. Different nature settings, such as urban street trees, parklands, tended woodlands, or wild woods, were not documented as having a significant difference in mental recovery in some studies (Van den Berg et al., 2014).

The structure of urban green space

Beyond simply the amount of urban green space, much scholarly attention has been paid to the impact of the structure of urban green space on mental well-being. The visual elements and structure of urban green space, in terms of compositional and configurational differences, can create various landscapes that might affect mental well-being. The question is which structural aspects of urban green space will have the greatest restorative value given the same amount of urban green space. For instance, some urban green spaces have complex arrangements of vegetation such as flowers, bushes, and trees, while other urban green spaces have simple arrangements such as a single tree and bushes. It is still unclear how these compositional and configuration changes might have differential impacts on mental well-being.

A previous study indicates that the arrangement of grass and trees has a higher level of restoration potential than does the decorative arrangement of flowers and water in small urban parks (Nordh et al., 2011). In terms of streetscapes, the number of trees and the existence of flower beds increase restoration likelihood ratings (Lindal and Hartig, 2015). Tall trees and landscapes with scattered and formally arranged plants have a higher restorative potential compared to landscapes with views of clustered plants (Kuper, 2017).

Research on the role of forest structure has burgeoned over the last decade. For example, Chiang et al. (2017) found the interior of forests to be more preferred and better able to promote stress recovery compared to forest edges and exteriors. In terms of density, forests with the highest vegetation density better promoted attention restoration than low-density vegetation. In line with this study, interior forests with closed views of the urban matrix had higher perceived restorativeness than forest edges with open or semi-closed views (Hauru et al., 2012). In contrast to previous studies, Gatersleben and Andrews (2013) illuminate that environments with a high level of prospect (e.g., clear fields of vision) and a low level of refuge (places to hide, such as densely wooded areas) can provide more mental restoration than environments with a low level of prospect and a high level of refuge.

Furthermore, forest environments with dense trees, sparse shrubs, and high-coverage herb layers can improve thermal comfort and ultimately lead to reduced physiological stress (Lin et al., 2022). For example, old-growth forests, which are more natural-looking (in the absence of direct signs of forest management), have a greater restorative effect than young forests (Simkin et al., 2020). However, Takayama et al. (2017) showed that whether or not forests were directly managed resulted in no significant difference for mental restoration.

The biodiversity of urban green space is a key component of how landscape structure affects mental well-being, since plant species richness and diversity determine our visual perception of the greenness. Higher biodiversity in urban areas may enhance mental well-being (Díaz et al., 2006). Although evidence of the direct association between health outcomes and biodiversity is limited, more frequent contact with various natural habitats and species-rich areas has a positive relationship with mental well-being (Sandifer et al., 2015; Wood et al., 2018). Also, there is a positive relationship between perceived biodiversity and site satisfaction that can moderate mental health and well-being (Southon et al., 2018). Higher biodiversity, both in urban and peri-urban areas, has greater positive perceived restorativeness and self-reported benefits on people who visit urban green space (Carrus et al., 2015).

Some observational studies have found an association between landscape spatial patterns and human well-being. Lee et al. (2008) investigated the effects of landscape pattern on neighborhood satisfaction and concluded that landscape patterns with well-connected and less fragmented or isolated patches were associated with greater neighborhood satisfaction. Chou et al. (2016) also concluded that large and continuous green-space patches improved the positive physiological and psychological responses of people. Tsai et al. (2018) investigated the relationship between landcover patterns and mental health in 50 U.S. metropolitan cities and discovered that landscape patterns (such as edge contrast, cohesion, and the distance between patches) were associated with self-reported frequent mental distress.

2.3.2 Research study design

This review has revealed that two primary research designs have been employed in studies that investigate the relationship between nature and mental well-being: experimental and observational studies. Generally, most experimental studies adopt laboratory and field experiments that verify the effect of a specific environmental intervention on mental well-being (see table 1). Lab experiments have been implemented under highly controlled conditions through different types of media. While many previous studies have created environmental conditions using images and videos, recent studies have begun to utilize virtual reality to simulate different environmental conditions. Virtual reality can create more realistic environments that enable participants to achieve a fully immersive and interactive experience during the experiment (Burdea and Coiffet, 2003; Rubio-Tamayo et al., 2017).

Many experimental studies have been conducted on-site within the sight of environmental interventions (Im et al., 2016; Sonntag-Öström et al., 2014; South et al., 2015). Experimental studies conducted in the field allow participants to move and walk around within the site areas. The duration of the environmental exposure within these types of studies ranges from minutes to hours within a given period of time.

Observational studies involve cross-sectional and longitudinal studies in which no environmental intervention takes place. Many studies have investigated how urban greenness around neighborhoods in everyday experience is associated with mental health and well-being (Beyer et al., 2014; van den Berg et al., 2017; Wang et al., 2019b; Wood et al., 2017). The vast majority of observational studies have employed cross-sectional methods that verify the relationship between mental health status and living environments at a specific point in time. Cross-sectional studies, however, cannot draw the temporal link between the neighborhood's natural environment and overall well-being as a result of the simultaneous assessment of exposure and outcome (Solem, 2015). To overcome this weakness, researchers employ a longitudinal study in which they repeatedly observe the mental well-being of the same individuals over a period of time, or they investigate how environmental changes through relocation (e.g., moving home) are associated with mental health status (Alcock et al., 2014).

The spatial scale of observational studies ranges from the neighborhood to the urban scale (see table 1). At the neighborhood scale, researchers measure environmental attributes at different scales (i.e., buffers) centered on respondents' homes. Some observational studies have instead employed the census block (or some other unique unit of districts by country and county) as a unit to characterize the urban environment at the neighborhood scale. The data from individual respondents are then nested within the group-level variables (e.g., urban environment variables). The temporal scale of the observational study ranges from a specific point in time to years (see table 1).

Table 1 Research study design and spatial and temporal scale

		Categories
Types of study	**Experimental study**	Laboratory experiment, Field experiment
	Observational study	Cross-sectional study, Longitudinal study
Scale	**Spatial scale**	On site scale < Neighborhood scale < Urban scale
	Temporal scale	Minutes/Hours < Days < Years

As a result of the literature review, two main methods have surfaced to evaluate respondents' mental health and well-being: psychological and physiological responses. The majority of observational studies have used a validated standard and a reliable psychological test (e.g., the Profile of Mood States) to examine psychological and mental health status, including perceived restoration, stress, anxiety, depression, mood state, and mental well-being. Several studies have evaluated mental health status using medical records such as diagnosis, prescription medication sales, and emergency room visits for mental health problems.

In experimental studies, both physiological and psychological status were widely used to measure mood status and stress level. Physiological mood and stress have been measured by skin conductance, heart rate, blood pressure, brain waves, salivary cortisol, and body temperature. The objective attention span test was also used to measure attention restoration using Digit Span Forward (DF) and the Digit Span Backward (DB) tests and Digit Letter Substitution Test (DLST). The psychological response assessments using validated instruments were also frequently utilized in experimental studies. In a pretest-posttest design, the evaluation of the environmental intervention effect was tested by the Positive Affect and Negative Affect Schedule (PANAS), Profile of Mood States (POMS), and Restoration Outcome Scale (ROS). However, the Perceived Restorativeness Scale (PRS) was mainly used in posttest-only research designs.

2.3.3 Mental health/well-being assessments

Table 2 Mental health/well-being measurements

Measurements	Instruments
Psychological response	Perceived Restorativeness Scale (PRS). Perceived Stress Scale (PSS), Psychological distress (Kessler Psychological Distress Scale), Self-reported physician-diagnosed depression or anxiety, Positive Affect and Negative Affect Schedule (PANAS), Profile of Mood States (POMS), Restoration Outcome Scale (ROS), Strengths and Difficulties Questionnaire (SDQ), Depression Anxiety and Stress Scales (DASS), RAND-36: Mental Health/Well-Being and Vitality Scores, Edinburgh Mental Well-being Scale (SWEMWBS), The Mental Health Inventory (MHI-5), Zuckerman Inventory of Personal Reactions (ZIPERS), Trier Social Stress Test (TSST)
Physiological response	Skin Conductivity Levels (SCL), Heart rate and blood pressure, Electroencephalogram (EEG), Electrocardiography (ECG), Salivary Cortisol, Body Temperature (BT), functional Magnetic Resonance Imaging (fMRI)
Medical records	Diagnosis, prescription medication sales, and emergency room visits for mental health problems
Objective attention span	Digit Span Forward (DF) and the Digit Span Backward (DB) tests

Measurements	Instruments
Digit Letter Substitution Test (DLST)	

2.4 Discussion

2.4.1 The role of spatial characteristics of urban green space on mental well-being

Research into urban green space and mental well-being has expanded exponentially over the course of recent decades. This review has shown that spatial characteristics of urban green space play a significant role in mental well-being. The initial ideas for investigating the relationship between human well-being and urban green space mainly started from a simple comparison between natural and urban environments. The majority of studies have used nature settings with window views, indoor plants, and experiences of nature, while urban settings tend to have environments with built-up areas, roads, and buildings (Li and Sullivan, 2016; Raanaas et al., 2011; Tsunetsugu et al., 2013). Beyond this dichotomous comparison, many epidemiological studies have investigated how the quantity of urban green space (e.g., amount and proximity) is associated with the mental well-being of urban residents (Astell-Burt et al., 2013; Nutsford et al., 2013). The amount and distance of urban green space from respondents' homes were derived from geospatial data, including the NDVI, the Land Cover dataset, tree canopy coverage, and land use data. In experimental studies, greenery at ground level (visibility) was measured by 360-degree view images (Jiang et al., 2014).

However, despite previous studies, the question of which types of urban green space — beyond simply the quantity of urban green space — most promote mental well-being remains open. Some research has further explored how different types of green landcover (e.g., forest, rangeland, agricultural land, and wetlands) are associated with mental well-being (Akpinar et al., 2016). Several experimental studies have attempted to uncover the relationship between types of urban green space and mental well-being using images from participants' eye views (e.g., forest, lake, park). But these pathways are far less studied for exploring the benefits of the structure of urban green spaces on mental well-being. The spatial characteristics of urban green space can vary widely in terms of compositional and configurational differences (With, 2019). Previous studies have focused on how the arrangement of landscape elements (e.g., trees, grass, water) can have an impact on restorative effects (Lindal and Hartig, 2015). For configurational aspects, much progress has been made in investigating how forest location (e.g., interior, edge, exterior) and biodiversity (e.g., plant species richness) can contribute to mental well-being (Carrus et al., 2015; Chiang et al., 2017). A handful of observational studies have focused on the effect of the spatial distribution of urban green space (e.g., size, distance, aggregation) on mental well-being (Tsai et al., 2018).

Table 3 Categories of spatial characteristics of urban green space

Spatial characteristics of urban green space	Green space exposure / Measurement
Presence of nature	Nature (nature experience, window view, indoor plants) vs. Urban (built-up areas, roads, buildings)
Amount of urban green space	Urban greenness: Normalized Difference Vegetation Index (NDVI), Land Cover dataset, tree canopy coverage, raster land use data, greenery at ground level (visibility)
Proximity (accessibility) of urban green space	Urban greenness: Normalized Difference Vegetation Index (NDVI), Land Cover dataset, raster land use data
Types of urban green space	Land Cover dataset, raster land use data, image from participants' eye view (e.g., forest, lake, park)
Structure of urban green space	The layout of the vegetation, forest location (e.g., interior, edge, exterior), biodiversity (e.g., plant species richness), configuration (e.g., size, distance, aggregation, landscape diversity)

2.4.2 Pathways of mental well-being and health

The spatial characteristics of urban green space affect human behavior and perception, which may contribute to mental health and well-being. There are several pathways through which green space can promote improved mental health (see figure 3). The results of the review verify that exposure to urban nature can promote mental restoration and stress recovery, while urban environments negatively impact mental health. The benefit of urban green space can be achieved by the experience of nature through window views and indoor greenery. The cumulative exposure to urban green space in everyday life significantly leads to enhanced mental well-being (Gilchrist et al., 2015).

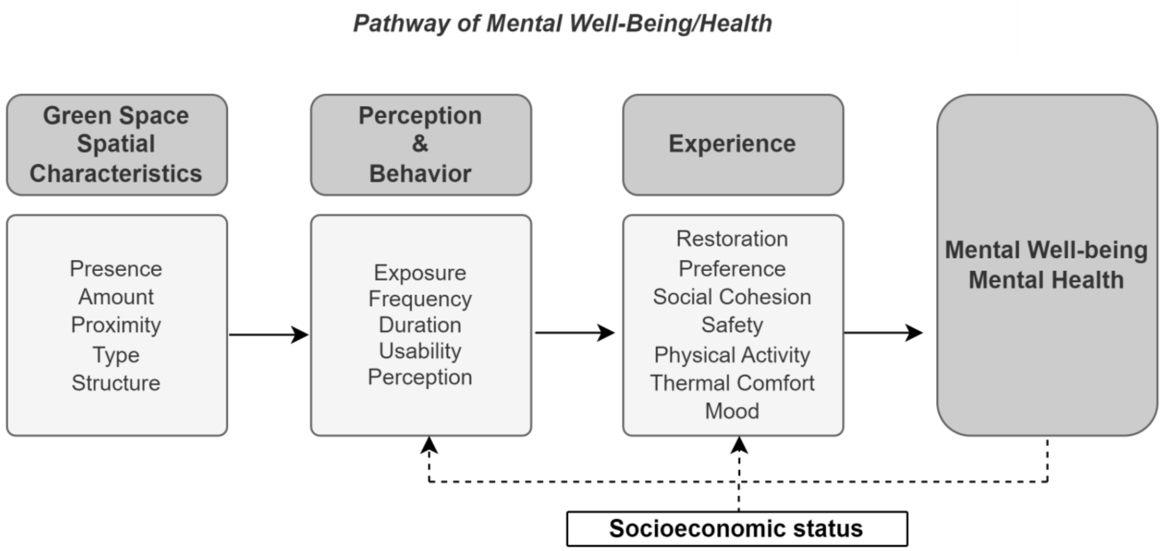

Figure 3 Pathways of mental well-being and health

The amount of urban green space plays a significant role in increasing the amount of exposure to the natural environment. Either the extent of nature within view or nature from neighborhoods within walking distance can improve mental restoration and the perception of safety while reducing mental health problems (Astell-Burt et al., 2013; Maas et al., 2009;

Olszewska-Guizzo et al., 2018). But the relationship between mental restoration and quantity of urban green space is not always linear. This relationship can be depicted as an inverted u-shape (Jiang et al., 2014). Furthermore, the amount of urban green space is also related to the time spent on visits to green space. The more neighborhood green space that exists, the more time is spent on visits to green space (van den Berg et al., 2017). To my knowledge, however, not many studies have investigated the mediation effect of the time spent on visits to green space between neighborhood greenness and mental health/well-being. The amount of neighborhood greenness also encourages urban residents to engage in physical activity (e.g., walking, jogging, or other forms of exercise). Few studies have examined the mediation effect of physical activity on greenness and mental health problems (Pun et al., 2018). Lastly, as urban green space can decrease the urban heat island effect, a large volume of urban tree canopy can improve psychological and physiological thermal comfort and subsequently improve mental well-being (Lin et al., 2022). In a similar vein, the accessibility of urban green space plays a significant role in increasing opportunities to visit (frequency) urban green spaces (Neuvonen et al., 2007). More frequent visits to urban green spaces promote physical activity and restorative experiences for urban residents (Roemmich et al., 2006). As types of urban green space (in terms of function) determine the usability and activity within the space (e.g., recreational purposes, social gatherings), these attributes lead to physical activity and social cohesion that can affect mental well-being (Fan et al., 2011; Wood et al., 2017). The structure of urban green spaces impacts people’s visual perception, which may influence their preferences and restorative potential (Chiang et al., 2017; Lindal and Hartig, 2015). As an outcome of the above pathways, the spatial characteristics of urban green space can contribute to mental and physical well-being.

In psychiatric epidemiology, socioeconomic status is closely linked to mental health since there is a noticeable difference between the mental health outcomes of the privileged and the disadvantaged (Ng et al., 2014). Several socioeconomic factors, including age, gender, income, education, and ethnicity, are commonly used as covariates and confounding variables in studies on mental health. (Andrusaityte et al., 2020; Mukherjee et al., 2017; Southon et al., 2018; van den Berg et al., 2017; Wang et al., 2019a).

2.4.3 Research study design

Based on the results of the review, I determined that experimental and observational studies were the two main research designs utilized in urban green space and mental well-being studies. These research designs are complementary. Experimental studies can test the specific and detailed environmental interventions that affect human perception and psychophysiological responses. Through the results of experimental studies, implications for restorative landscape design can be derived. Experimental studies have mainly been conducted on site scale studies, measuring the short-term effects of psychophysiological responses. Very few studies have attempted to verify the long-term effects of urban green spaces on mental health. The researcher may assign the environmental exposure using images, video, virtual reality, and field experiments. In particular, a growing body of research has conducted virtual reality experiments because the field experiment condition was limited due to disturbances such as weather, people, or vehicles (Gao et al., 2019; Li et al., 2020; Yu et al., 2018).

Observational studies provide information on mental health and well-being outcomes without any environmental intervention effects in ‘real world’ scenarios. Through observational studies, we can understand how urban green space is associated with mental health and well-being in urban or neighborhood-scale environments. The vast majority of observational studies adopt cross-sectional methods, which observe the effects of urban green space on mental well-being at a specific point in time. Only a few researchers have attempted to carry out longitudinal studies that track the effects of urban green space on mental well-being over time. I also found that few studies have attempted to use objective measurements of mental health and well-being (Roe et al., 2013; Ward Thompson et al., 2012).

2.5 Conclusion and future research

This literature review investigated the current state of knowledge on the relationship between the spatial characteristics of urban green space and mental well-being. The present review provides a better understanding of the pathway to mental well-being by exploring how the spatial characteristics of urban green space influence human perception and behavior. The results of this review indicate that there are five spatial characteristics that shape the pathways for mental well-being: presence of nature, amount of urban green space, proximity of urban green space, types of urban green space, and structure of urban green space. These characteristics determine the exposure, frequency, duration, usability, and perception of urban green space that leads to mental restoration, preference, social cohesion, safety, physical activity, and thermal comfort. This investigation identified a knowledge gap that explains why the spatial characteristics of urban green space can contribute to mental well-being and mental health for urban residents.

This review found that many previous studies have focused on the role of nature on mental well-being, comparing urban environments with natural environments. In addition, the vast majority of epidemiological studies have mainly addressed the effects of the quantity of urban green space (e.g., amount, proximity) on mental well-being. There is growing evidence on how the structure of urban green space impacts human perception and behavior that might lead to mental health and well-being. Beyond just addressing the existence of urban green space, future research should focus on the impact of the structure of urban green space on mental well-being. This approach would enable landscape and urban planners to maximize the benefits of existing nature for mental well-being, especially in metropolitan areas where the provision of urban green space is limited.

As a result of this review, this dissertation aims to explore the role of the structure of urban green space on mental well-being with a focus on green space biodiversity and landscape patterns. The study on green space biodiversity is significant as plant and animal species richness play a pivotal role in visual preference and perception as part of restorative mechanisms. Through the experimental research design, the causal effect of spatial composition on mental well-being was examined. In addition, the study on landscape patterns and mental well-being is a crucial part of this dissertation. The configuration and composition of urban green space might be associated with mental well-being as landscape patterns determine restorative mechanisms, including exposure, frequency, and usability of urban green space. Through the observational research design, this dissertation illuminates the role of landscape patterns on mental well-being in “real-life” settings without any interventions.

Chapter 3 - [1]The Restorative Effects of Campus Landscape Biodiversity: Assessing Visual and Auditory Perceptions Among University Students

3.1 Introduction

University students are at risk for mental health problems, including stress, anxiety, mental fatigue, and depression (Auerbach et al., 2018; Dishman et al., 2010; Nyer et al., 2015; Rawson et al., 1994). Although many universities offer mental health treatment and counseling programs, the vast majority of students are reluctant to take advantage of them due to the barriers caused by personal and public stigma (Eisenberg et al., 2009). Currently, there is a growing interest in the role of the campus environment as an intervention to reduce mental health risks and improve the psychological wellbeing of university students. Students spend most of their time on campus almost every day and this is where their various social engagements occur (e.g., walking, playing, resting, and restoring) (Gulwadi et al., 2019). A university campus is a usual daily destination for university students, and is a place of recurring patterns and organized social activities. The campus environment may have the potential to help students improve their mental health and well-being in everyday college life (Gulwadi et al., 2019; Liprini and Coetzee, 2017; McFarland et al., 2008; Seitz et al., 2014; Van Den Bogerd et al., 2018). In particular, a dose of nature plays a critical role in improving attention restoration, stress reduction, and academic

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performance for students (Akpinar, 2016; Amicone et al., 2018; Li and Sullivan, 2016; van Dijk-Wesselius et al., 2018).

Several theoretical backgrounds helped to provide a better understanding of the linkage between campus landscape and the psychological benefits for students. It is a widely held view that psychological restoration can be achieved in natural settings. According to the biophilia hypothesis, humans are inherently affiliated with nature (life and lifelike processes) as a part of the consequences of evolution (Kellert, 1995). Moreover, the attention restoration theory (ART) suggests that nonthreatening nature can be a medium for restorative environments, which leads to involuntary attention restoration (Kaplan and Kaplan, 1989). Unlike voluntary attention (directed attention) which requires additional effort and could be depleted through constant use (Kahneman, 1973; Mattila et al., 2020), the natural environment can evoke effortless attention and allow restoration of depleted voluntary attention and mental fatigue. Another important theory regarding the restorative environment is the stress reduction theory (SRT), which claims that the natural environment can contribute to the recovery of psychophysiological stress (Ulrich et al., 1991). When perceiving the surrounding environment, a person determines an initial affective reaction (e.g., like, dislike) which subsequently leads to cogitative (appraisal of the scene; e.g., beneficial or harmful) and emotional arousal (e.g., negative or positive emotions) (Ulrich, 1983). This in turn affects physiological arousal (e.g., relaxation) and behavior (Marselle, 2019; Ulrich, 1983).

Though much work has addressed the role of the school landscape on students' mental health, studies often view campus greenness as merely open spaces with vegetation or greenery on the basis of simple categorizations, without a sufficient consideration of more diverse landscape types and ecological functions (Carrus et al., 2015; de Vries and Snep, 2019). Indeed, the compositional and layout differences in the natural environment can lead to a different level of biodiversity (Chiang et al., 2017). Campus landscapes continue to be a symbol of greenness (Scholl and Gulwadi, 2018) and have the potential to function as habitats for plants and animals (Lawton, 1983; MacArthur and MacArthur, 1961).

More biodiverse natural environments have greater restorative benefits than less biodiverse environments (Carrus et al., 2015; Fuller et al., 2007; Wolf et al., 2017; Wood et al., 2018). Based on the ART, more biodiverse environments may lead to having fascinating stimuli and the sense of being away (Marselle, 2019). In a related vein, biodiverse natural environments can have restorative potential on one's stress recovery. According to the SRT, visual properties have an impact on aesthetic preference and interest, which in turn affects physiological responses (e.g., relaxation) (Marselle, 2019; Ulrich, 1983). In particular, a biodiverse environment is associated with visual complexity as a higher number of plant species (e.g., colors, heights, leaf shapes) is related to a higher visual complexity in a landscape (Young et al., 2020). But, it is also argued that moderate visual complexity is more desired in aesthetic preference and pleasantness than low and high complexity resulting in an inverted U-shaped relationship (Ulrich, 1983).

The biodiversity of green space can enhance people's sense of nature not only through vision but also other sensory modalities like auditory stimuli (Lindquist et al., 2020). Natural sound (e.g., birdsongs, water, and wind) can induce a pleasant auditory experience that may enhance cognitive performance as well as restoration in mind (Abbott et al., 2016). This study attempts to bridge two lines of research on the restorative potential for students on campus by linking the school greenness with biodiversity, as well as with the role of biodiversity as multisensory stimuli (visual and auditory) on the restorative potential.

This study examined three main hypotheses: (1) A group of students exposed to a high biodiversity environment has higher restorative and positive mood states than a group of students in a low biodiversity environment; (2) sound exposure with visual stimuli moderates the effects of restorative and positive mood states on students, and; (3) there is an interaction effect of the combination of visual and auditory stimuli on restorative and mood states in students.

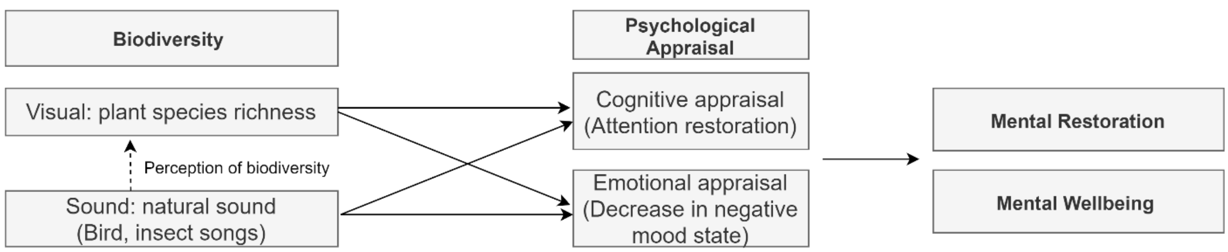


Figure 4 Conceptual framework of the study

3.1.1 Literature review

Campus landscapes as a restorative environment: The campus environment, including buildings and its outdoor spaces (e.g., open spaces, green spaces, recreation centers) can be considered as interactive learning places where students develop, are restored, and play (Gulwadi et al., 2019; Kuh, 2011). It is a widely held view that campus green spaces might be linked to a restorative potential for students (Gulwadi et al., 2019; Hipp et al., 2016; Scholl and Gulwadi, 2018). In attention restoration theory (ART), Kaplan and Kaplan (1989) theorized that involuntary recovery from directed attention fatigue can be achieved by four components—being away, fascination, extent, and compatibility. Campus landscapes can be a medium for those conditions. Students may encounter different types of green spaces, a tree-lined walking trail with grass, shrubs, and flowers, when they are walking on paths between buildings. The natural environment of a campus enables students to escape from daily disturbances while they take a break. Natural settings with a vegetation enclosure (e.g., forest trails, woodlands) could increase the possibility of such a sense of being away from daily worries and concerns (Hauru et al., 2012; Kaplan and Kaplan, 1989). Aesthetically pleasing green areas could promote an experience of soft fascination, which evokes involuntary attention (Felsten, 2009). Viewing colorful flowers in campus flowerbeds or the seasonal changes of deciduous trees contributes to the sense of preference and restorative potential (Hoyle et al., 2017; Kuper, 2020).

Effects of biodiversity on psychological wellbeing and restoration: A growing body of studies has been carried out to explore the role of biodiversity on people's mental restoration. Several experimental studies using the on-site survey method concluded that a higher biodiversity of green space contributes to a better restorative and psychological status (Carrus et al., 2015; Fuller et al., 2007; Wood et al., 2018). The species richness (plant, bird, and insect) is positively associated with restorative benefits (Wood et al., 2018). Greater biodiversity could contribute to a greater degree of soft fascination enabling people to enter a stage of involuntary attention (Cook et al., 2019; Kaplan and Kaplan, 1989). The effect of plant species richness on the positive and negative indicators of mental wellbeing is also confirmed in a recent experimental study using video stimuli via an online-based survey (Wolf et al., 2017). Despite a number of studies asserting the positive effect of biodiversity on psychological health, the effect of green space biodiversity on restorative potential currently remains open. Some studies argue that green space biodiversity had a negative or no relationship with psychological mental wellbeing-related determinants (Chang et al., 2016; Dallimer et al., 2012), and psychological benefits of green space biodiversity may rely on the individual's ability to perceive biodiversity (Dallimer et al., 2012; Southon et al., 2018).

Effects of auditory-visual stimuli on psychological restoration: Another trend in studies linking green space and psychological restoration is that the studies tend to solely focus on the aspect of visual perception of biodiversity, even though sight is not the only sense that affects the psychological response of humans in urban green spaces (Grahn and Stigsdotter, 2010). The restorative effect can be partially explained by sound stimuli. Previous studies have shown that natural sound is positively associated with psychological and physiological benefits while anthropogenic sound (e.g., motorized vehicles) is negatively associated with these benefits (Abbott et al., 2016; Alvarsson et al., 2010; Benfield et al., 2014; Payne, 2009). In particular, natural sounds from living things such as bird and insect songs can generate restorative benefits. Bird songs and calls have restorative effects in attention restoration and recovery from stress (Fisher et al., 2021; Ratcliffe et al., 2016; Shu and Ma, 2018) through the process of positive affect and reduced arousal (Ratcliffe et al., 2013). Along with psychological restoration, bird songs can contribute to physiological stress recovery (e.g., skin conductance level, heart rate variability) (Alvarsson et al., 2010). Also, it should be noted that insect songs have the same restorative effect as bird songs by reducing mental fatigue and stress (Shu and Ma, 2017; Zhang et al., 2017b).

Senses beyond vision can lead to a greater scope for one's perception and interaction with the environment (Lindquist et al., 2016). Information from visual and aural senses can strengthen one another and offer a more authentic experience (Deng et al., 2020b; Hedblom et al., 2019; Lindquist et al., 2020; Song et al., 2018). The combination of the physical environment and a personal interpretation of its soundscape can make restorative soundscapes (Payne and Guastavino, 2018). But the mechanism between auditory stimuli and restorative effect has been understudied. Few attempts have been made to illuminate the effects of auditory-visual combinations on restorative potential. Deng et al. (2020b) found that the integration of visual (e.g., natural water, shrubs) and auditory stimuli (e.g., flowing water, birdsong) can promote better restorative potential and preferences than the single factor stimuli. In particular, Zhao et al. (2018) highlighted the importance of the visual association of a sound for landscape design in facilitating mental restoration potential. Spatiotemporal congruence in visual and sound exposure could generate a more realistic environment for participants (Lindquist et al., 2016). However, while much emphasis has been placed on the multisensory approach, the integration effect of visual and auditory stimuli on students' mental restoration from site biodiversity has remained largely unexplored. The multisensory approach related to site biodiversity has to be examined since natural sound creates a stronger perception of site biodiversity (e.g., perceived biodiversity) than does sole visual stimuli (Gunnarsson et al., 2017; Lindquist et al., 2020).

3.2 Methods

3.2.1 Study design

This study used a four-group pre-posttest-randomized experiment design (2×2 factorial design) on a group of university students (N=319) to compare high-low biodiversity as well as visual-auditory stimuli of biodiversity on restorative and mood states. We used an online survey platform incorporating YouTube-based 360-degree view videos containing two different environmental settings on a university campus. One had a higher biodiversity environment consisting of native meadow plants and tall grasses and the other had a lawn yard with a low biodiversity environment (see more images in the supplementary document). The total plant species richness in a high biodiversity area is 29; 6 tree, 22 herbaceous/shrub, and 1 grass species. In a low biodiversity environment setting, a total of 5 plant species were found: 2 tree, 2 herbaceous/shrub, and 1 grass species (see table 4). The two environmental settings were shown with the presence or absence of sound. Subjects were randomly assigned to view one of four different environmental conditions: (1) low biodiversity with no sound, (2) high biodiversity with no sound, (3) low biodiversity with sound, (4) high biodiversity with sound (Figure 5). We measured the restorative status and mood status (tension, depression, fatigue) at the pre-intervention (T1: baseline) and post-intervention (T2: after environmental exposure) from one of the four environmental conditions. The total intervention exposure time per subject was six minutes.

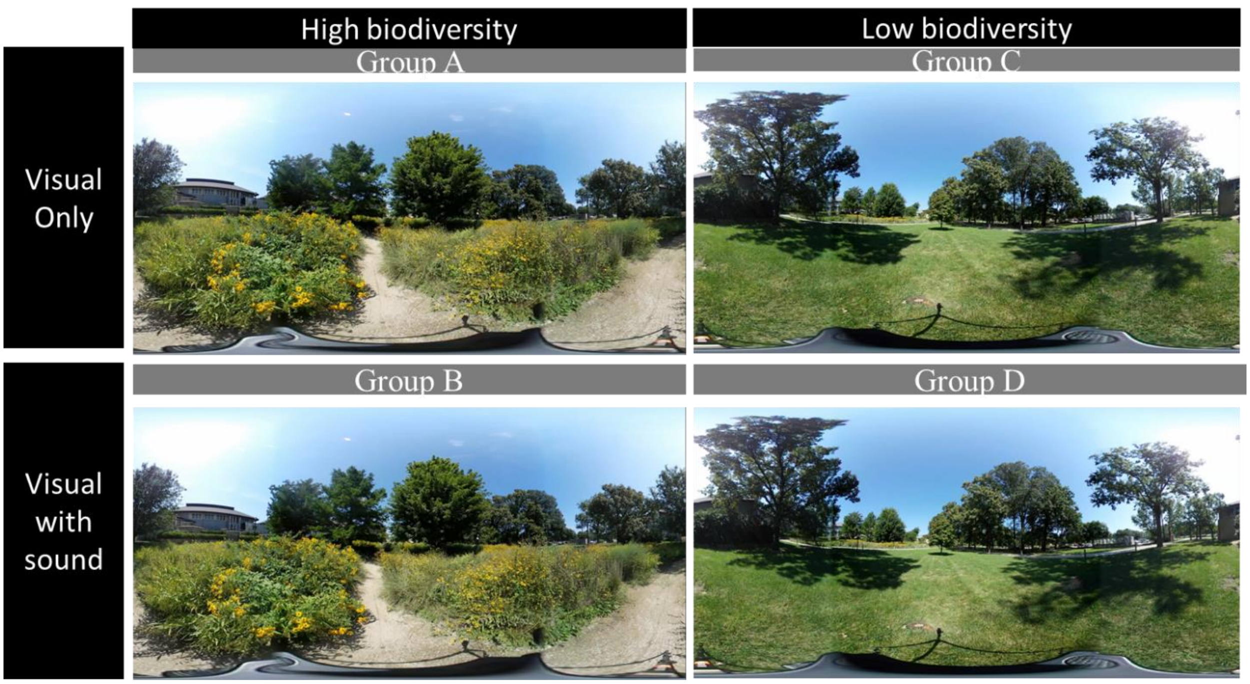


Figure 5 Experiment treatment (2×2 Factorial design)

Table 4 Plant species richness in two environment settings

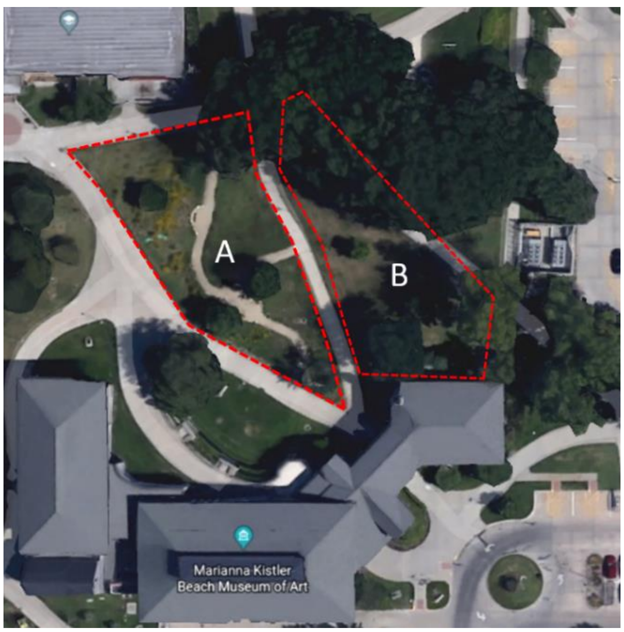
Environment	Plant species richness
Low biodiversity	• Tree (2 species): *Carya illinoensis, Acer Rubrum* • Herbaceous/Shrubs (2 species): *Taxus sp, Viburnum sp* • Grass (1 species): *Poa pratensis*

Environment	Plant species richness
High biodiversity	• Tree (6 species): *Sapindus saponaria, Acer saccharinum, Taxodium distichum, Ulmus parvifolia, Juniperus virginiana, Quercus muehlenbergii* • Herbaceous (22 species): *Chasmanthium latifolium, Monarda fistulosa, Rudbeckia subtomentosa, Aster drummondii, Elymus villosus, Diarrhena americana var.obovata, Schizachyrium scoparium, Bouteloua curtipendula, Asclepias tuberosa, Rudbeckia triloba, Asclepias speciosa, Asclepias sullivantii, Baptisia australis var. minor, Silphium laciniatum, Echinacea purpurea, Dalea purpurea, Solidago rigida, Salvia pitcher, Glandularia canadensis, Oenothera missouriensis, Coreopsis tinctoria, Carex blanda* • Grass (1 species): *Bouteloua dactyloides* • ETC: Several weeds (weed tree and pigweed–amaranth–being the most noticeable)

3.2.2 Study subject, setting, and procedure

A total of 319 university students (male: 219, female: 100) were recruited and participated in the online survey via the Amazon Mechanical Turk™ services (https://www.mturk.com). Only students currently residing and studying in the United States were selected as research subjects. Among them, graduate students were the majority (graduate: 277, undergraduate: 42). Participants were ethnically diverse consisting of 64.6% White, 22.9% Black, 9.7% Asian, and 2.8% Latino. Age groups mostly ranged from 18 to 33 years old (78.1%) and 56.1% of respondents were married. The household income ranged from $30,000 to $69,999 (64.5%). The average duration of the survey was 14 minutes. This research was approved by the Kansas State University Institutional Review Board (IRB).

Two environmental settings on campus were recorded with Samsung gear 360, which enabled us to record a 360-degree view. This view gives people a more real and immersive environment than the conventional 2D video, minimizing disturbance (e.g., weather, noise, and people) and maintaining the consistency of the environment (seasonal changes in the environment). Two videos were taken at 2 pm, on August 1^{st} in 2019 on a sunny day with a clear sky (see Figure 5). One had a higher biodiversity environment consisting of native meadow plants and tall grasses (Site A: Native meadow garden), the other had a lawn yard with a low biodiversity environment (Site B: Lawn area). The two environments were recorded at a 4K resolution (4096 × 2048 pixels) at 24 frames per second (FPS) with an internal microphone (128kbps, two audio channels). Two video clips recorded sites A and B with a spatiotemporal congruence. Both sites had similar sound conditions: insect sounds, wind-induced vegetation sounds, and birdsong. Insect sounds were dominant at both sites.



The experimental site (A): High biodiversity (Native meadow garden)

The control site (B): Low biodiversity (Lawn area)

Figure 6 Study site and experimental setting

Participants watched video clips linked to a YouTube URL in the Qualtrics program. The video ran for six minutes and presented one of the four environment settings. The length of exposure to the environment by previous studies ranged from 6 minutes to 10 minutes (Browning et al., 2020; Jiang et al., 2014; Karmanov and Hamel, 2008; Wang et al., 2016; Yu et al., 2018).

In this study, the shortest duration (6 minutes) was used to minimize the time of the survey as this experiment was conducted through an online platform. Before the environmental exposure, we asked participants to describe their current restorative and mood states (T1). Then, a total of 319 participants were randomly assigned to view for six minutes one of the four types of environment recorded by the 360-degree view camera. After watching the video clips (T2), we again requested participants to describe their restorative and mood states. At the end of the experiment, participants were also asked to indicate perceived species richness and socioeconomic status (e.g., gender, age, education, ethnicity, income, marital status). The experiment was conducted from August to September in 2020.

All subjects were asked to follow a specific procedure, including adjusting the video resolution to full-screen high-quality (1080p), turning on the sound on the computer, blocking noise from inside and outside of the room, and using the Virtual Reality (VR) mode on their PC which enabled them to look around the 360-degree view of the video using their mouse. Added to these, we implemented several safeguard procedures in order to ensure the validity of the study. First, any duplicate survey responses from the same respondent were excluded from the sample, and second, we excluded responses from the participants who did not complete watching the video or skipped it identified by using a simple verifying question in the middle of the video lapse (e.g., a random card number appearing for a few seconds).

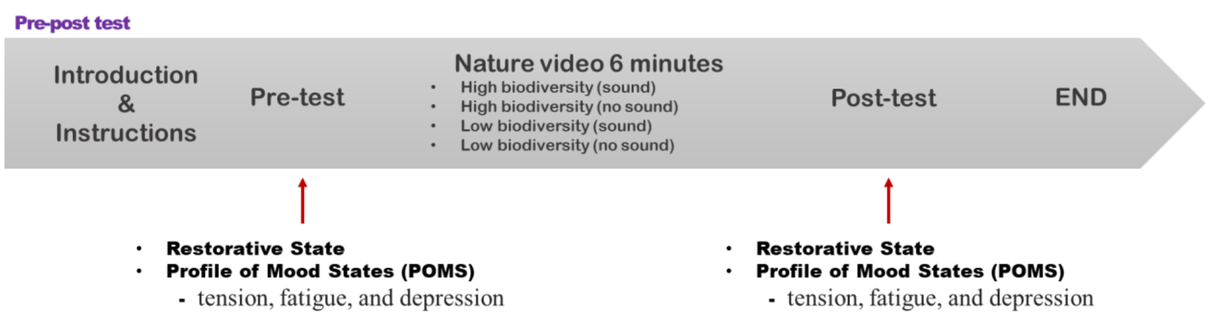


Figure 7 Study process

3.2.3 Data and variables

Restorative state: This study employed 9 items of the restorative state scale (RSS) created by Van den Berg et al. (2014), measuring restorative state using a five-point Likert scale (1 = Do not feel at all; 5 = Feel very strongly). This questionnaire included 9 questions, such as "My mind is not invaded by stressful thoughts." RSS has been developed on the basis of Kaplan and Kaplan (1989)'s attention restoration theory (ART). When it comes to the measurement of one's restoration, the perceived restorativeness scale (PRS) by Hartig et al. (1997b) has been widely used in similar studies using questionnaires representing four components; coherence, fascination, being away, and compatibility. As PRS can only evaluate environmental settings (e.g., on-site, video, photo image) (Hartig et al., 1997a), it is unsuitable to measure changes in the restorative state over time (Van den Berg et al., 2014). Thus, the PRS has mostly been used in posttest-only design studies. On the other hand, RSS focuses on capturing overall experiences of nature ('I feel connected to the natural world') and measuring distinct levels/functions of the restorative experience of nature ('I can make space to think about my problems') (Van den Berg et al., 2014).

Mood state: Measurements of mood states were taken from the Short Form of The Profile of Mood States (POMS-SF) representing tension, anger, fatigue, depression, esteem-related affect, vigor, and confusion (Curran et al., 1995). In this study, three negative aspects of mood state, including tension, fatigue, and depression were selected for the following reasons. First, these are the most prevalent negative mood states experienced by students during their academic life at a university (Guan and Duan, 2020; Ibrahim et al., 2013; Ratanasiripong et al., 2010). Second, the total number of questionnaires was carefully considered. As the total number of items on the original POMS-SF is 37, the pre-posttest study design needs to have at least 74 questions. Since a longer version of the questionnaire is more likely to yield lower response rates from participants (Deutskens et al., 2004), 18 items from three negative mood states were selected. This study also reduced the 7-point Likert format to a 5-point format. The online-based survey can induce greater cognitive demands and fatigue that lead to poor-quality answers (Savage and Waldman, 2008). A 5-point format can help reduce the "frustration level" from respondents and increase the response rate (Babakus and Mangold, 1992). In addition to this, considering the above reasons, we selected 18 questions from tension, fatigue, and depression (a total of 36 questions in the pre-posttest). Each dimension consisted of 4-6 questions measured by a 5-point Likert scale (1 = Not at all; 2 = A little; 3 = Moderate; 4 = Quite a lot; 5 = Extremely). Total scores for each dimension on mood state were averaged from the aggregation of its subscales.

Perceived species richness: Previous studies have demonstrated that perceived biodiversity was assessed by using the question "How many different types of plant/bird/butterfly species are in this environment?" with a five- or seven-point Likert scale (e.g., 1: 1-9 species, 5: 51-100 species) (Dallimer et al., 2012; Marselle et al., 2016; Southon et al., 2018). This study, however, mainly focused on the perceived plant species richness for the measurement of perceived biodiversity since animal and bird species were barely recognized through the video in our experiment setting. In addition to this, the perception of plant species richness is the most visible component of biodiversity that people can accurately assess (Fuller et al., 2007). Perceived plant species corresponds well to actual biodiversity level (Qiu et al., 2013) and represents the overall characteristic of site biodiversity (Gould, 2000).

In this study, multiple closed-ended questions were used to measure the biodiversity perceived by asking people to answer: "How many different kinds of trees can you find in the video?", "How many different kinds of herbaceous/shrubs can you find in the video?", and "How many different kinds of grass can you find in the video?". Responses were the assessment of the relative difference between plant species (1 = All the same to 5 = Many different kinds). Perceived plant species richness was averaged from the aggregation of each dimension. We asked participants to answer the degree of difference between plant species rather than asking the number of plant species. As the duration of environmental exposure in this study is relatively shorter (6 minutes) than the on-site experiment (hours), it is entirely possible that it is hard for participants to recall a list of plant species in the video. In addition to this, since participants cannot zoom in as far as they would like to, this deters people from calculating the number of plant species. In previous studies using a computer-simulated environment, perceived species richness was assessed through the degree of the perception/agreement on plant species richness toward the simulated environment— "Do you think there are many types of vegetation in this landscape? (e.g., scale from 1= A little to 5 = A great deal) (Gyllin and Grahn, 2005; Lindquist et al., 2020; Phillips and Lindquist, 2021; van den Berg et al., 1998).

Other variables: The socioeconomic status of respondents was collected and included gender, age, education, ethnicity, household income, and marital status.

Table 5 Summary of constructed variables

Variables		Description		Type
Response variables				
Psychological response	Restorative state	Restorative state scale (RSS)		Categorical variables
	Mood state	Short Form of The Profile of Mood States (POMS-SF) tension, fatigue, and depression		Categorical variables
Explanatory variables				
Environment variables	(Actual) Plant species richness	• High biodiversity (29 species richness)	• Low biodiversity	Binary variables

Variables		Description		Type
			(5 species richness)	
	Perceived plant species richness	Types of plant species • Trees • Herbaceous/Shrubs	• Grass	Categorical variables
	Natural sound	• Natural sound	• No sound	Binary variables

3.2.4 Statistical analysis

The following statistical analyses were performed to test our hypotheses: First, a Cronbach's α and confirmatory factor analysis (CFA) were conducted to test internal consistency and determine the validity of each item's factor loadings based on theory or hypotheses (Hair et al., 1998). The Cronbach's α was calculated using the reliability analysis in IBM SPSS 25. In the CFA analysis, we evaluated the scale validity of each psychological variable using the R studio version 1.2.1335 of the package "Lavaan" (Rosseel, 2012). Second, we conducted a repeated measures analysis of variance (repeated measures ANOVA) to verify the effects of pre- (T1: baseline) and post-intervention (T2: after watching the video) on restoration and mood states with their interactions (biodiversity and the presence of sound). Third, a two-way analysis of covariance (ANCOVA) analysis was conducted to test the differences in restoration and mood states among the four groups, making the pretest results covariates and controlling the baseline of each psychological response. Fourth, the linear regression was performed to find the association between perceived species richness and psychological responses. Last, a one-way ANOVA was conducted to examine the difference in perceived species richness among the four groups. All analyses were conducted through the general linear model (GLM) using IBM SPSS

25. The level of significance selected for this study was both an 0.01 level and an 0.05 level (the p-values).

Validity and reliability of the scales: The Cronbach's α was computed to test the internal consistency of all scales of restoration, mood states, and perceived species richness from respondents. All the items in the restoration and mood states indicated a high consistency (all values were over 0.7) in both the pretest and posttest. As a rule of thumb, a value over 0.70 in the Cronbach's α test was generally accepted as internally consistent (Nunnally, 1994)

The CFA was conducted to evaluate how well each item of the questionnaire represented the psychological responses. In this study, the overall model fit was considered to be a good fit when the following indices were met: The chi-square ($\chi 2$) $p > 0.05$, the comparative fit index (CFI) > 0.90, the Tucker Lewis index (TLI) > 0.95, the root mean square error of approximation (RMSEA) < 0.08, the standardized root mean square residual (SRMR) < 0.08 (Hooper et al., 2008; Kline, 2015). Since the restorative state in both the pretest and posttest did not demonstrate a good model fit, two items which had the lowest factor loadings were removed and the CFA was recomputed. In the pretest model, the model fit of the restorative state was acceptable, CFI = 0.907, TLI = 0.860, RMSEA = 0.117, SRMR = 0.062. The result of the mood state demonstrated a good model fit, CFI = 0.971, TLI = 0.966, RMSEA = 0.066, SRMR = 0.022. In the posttest model, the restorative state reveals a good model fit, CFI = 0.951, TLI = 0.926, RMSEA = 0.086, SRMR = 0.047. In the mood state, the model fit appeared to be good, CFI = 0.967, TLI = 0.962, RMSEA = 0.074, SRMR = 0.020. The factor loadings from all CFA models were greater than 0.50 and statistically significant ($p < 0.05$), meaning that all items of the questionnaire well represent each factor of restorative and mood states.

3.3 Results

3.3.1 Descriptive statistics of subjects' demographics

Table 6 Descriptive statistics of subjects' demographics

		Total	Low biodiversity			High biodiversity		
		319 (100%)	No sound	Sound	Total	No sound	Sound	Total
Gender	Male	219 (68.7%)	53	52	105	56	58	114
	Female	100 (31.3%)	26	28	54	24	22	46
Age	18-21	32 (10.0%)	9	7	16	6	10	16
	22-25	108 (33.9%)	29	26	55	28	25	53
	26-29	54 (16.9%)	16	17	33	7	14	21
	30-33	55 (17.2%)	13	12	25	15	15	30
	Above 34	70 (21.9%)	12	18	30	24	16	40
Education	Undergraduate	42 (13.2%)	10	8	18	12	12	24
	Graduate	277 (86.8%)	69	72	141	68	68	136
Ethnicity	Asian	31 (9.7%)	10	13	23	3	5	8
	Black	73 (22.9%)	13	17	30	21	22	43
	Latino	9 (2.8%)	2	3	5	2	2	4
	White	206 (64.6%)	54	47	101	54	51	105
Household Income	$10,000 – $19,999	34 (10.7%)	10	10	20	7	7	14
	$20,000 – $29,999	42 (13.2%)	17	9	26	12	4	16
	$30,000 – $49,999	99 (31.0%)	17	25	42	26	31	57
	$50,000 – $69,999	107 (33.5%)	26	23	49	26	32	58
	Above $70,000	37 (11.6%)	9	13	22	9	6	15
Marital status	No	140 (43.9%)	33	38	71	35	34	69
	Yes	179 (56.1%)	46	42	88	45	46	91

The demographic characteristics of the subjects are described in table 6 by the four different environmental conditions. Participants were mainly drawn from those who are male, graduate students, and from a white ethnic background. Though these demographic characteristics show a dominance over other demographic groups, the number of participants from each demographic group was roughly evenly distributed (25% each) in the four different environment settings.

3.3.2 The effects of the environmental intervention on psychological responses: Repeated-measures ANOVA (Within subject comparisons)

Table 7 Descriptive statistics for restorative and mood states by four different environmental settings in the pretest (T1) and posttest intervention (T2)

		Low biodiversity			High biodiversity			
		No sound (n=79)	Sound (n=80)	Total (n=159)	No sound (n=80)	Sound (n=80)	Total (n=160)	Total (n=319)
Pretest (T1)	Restorative state	3.54 (0.73)	3.51 (0.74)	3.52 (0.74)	3.37 (0.86)	3.36 (0.72)	3.44 (0.77)	3.45 (0.77)
	Tension	2.95 (1.10)	2.75 (1.23)	2.85 (1.17)	2.68 (1.21)	2.69 (1.19)	2.69 (1.19)	2.77 (1.18)
	Fatigue	2.97 (1.17)	2.81 (1.21)	2.89 (1.19)	2.74 (1.25)	2.63 (1.19)	2.68 (1.22)	2.79 (1.21)
	Depression	2.88 (1.21)	2.67 (1.23)	2.77 (1.22)	2.64 (1.24)	2.67 (1.22)	2.66 (1.23)	2.72 (1.22)
Posttest (T2)	Restorative state	3.52 (0.76)	3.35 (0.82)	3.44 (0.79)	3.40 (0.87)	3.34 (0.77)	3.37 (0.82)	3.41 (0.81)
	Tension	2.73 (1.17)	2.69 (1.25)	2.71 (1.21)	2.64 (1.23)	2.59 (1.20)	2.61 (1.21)	2.66 (1.21)
	Fatigue	2.85 (1.21)	2.75 (1.31)	2.80 (1.25)	2.68 (1.29)	2.62 (1.25)	2.65 (1.27)	2.72 (1.26)
	Depression	2.73 (1.21)	2.68 (1.32)	2.70 (1.26)	2.64 (1.30)	2.62 (1.28)	2.63 (1.28)	2.67 (1.27)

Notes: values are mean (min: 1; max: 5), with standard deviation inside parentheses.

Restorative state: The results showed that time and biodiversity had no significant effects on the restorative state between the pre-test and post-test conditions, respectively, p = 0.167. All the interactions between time and other factors (e.g., biodiversity, sound) were also not statistically significant, $p = 0.477$ (see table 8).

Tension: In the case of tension, the results showed that time had a significant effect on tension at the 0.01 level, $F(1,315) = 14.783$, $p < 0.001$, $\eta 2 = 0.045$. The level of tension was lower at the posttest condition than at the baseline condition, mean change (pretest - posttest) = 0.110, 95% CI = 0.051–0.159. The interaction term (Time × Biodiversity × Sound) was statistically significant at the 0.05 level, which indicates that the level of biodiversity and the presence of sound interacted with the effect of time in the case of tension.

Fatigue: In terms of fatigue, there was a significant effect of time on fatigue, $F(1,315) = 4.129$, $p < 0.05$, $\eta 2 = 0.013$. The level of fatigue decreased more significantly at the posttest condition than at the baseline condition, mean change (pretest - posttest) = 0.070, 95% CI = 0.002–0.127. There was no significant interaction term between time and other factors.

Depression: The effect of time on depression was marginally significant, $F(1,315) = 3.168$, $p < 0.1$, $\eta 2 = 0.010$. The level of depression was lower at the posttest condition than at the baseline condition, mean change (pretest - posttest) = 0.050, 95% CI = -0.005–0.106. The interaction term (Time × Biodiversity × Sound) was statistically significant at the 0.05 level. The level of biodiversity and the presence of sound interacted with the effect of time in the case of depression.

Table 8 Results of repeated-measures ANOVA for biodiversity, sound, and the combination effects

Variables	Interaction	Sum of squares	df	Mean square	F	p-value	Partial Eta Squared
Restorative state	Time	.264	1	.264	1.916	.167	.006
	Time × Biodiversity	.312	1	.312	2.267	.133	.007
	Time × Sound	.336	1	.336	2.442	.119	.008
	Time × Biodiversity × Sound	.070	1	.070	.507	.477	.002
Tension	Time	1.753	1	1.753	14.783	.000***	.045
	Time × Biodiversity	.173	1	.173	1.462	.227	.005
	Time × Sound	.097	1	.097	.817	.367	.003
	Time × Biodiversity × Sound	.517	1	.517	4.359	.038**	.014
Fatigue	Time	.659	1	.659	4.129	.043**	.013
	Time × Biodiversity	.137	1	.137	.857	.355	.003
	Time × Sound	.123	1	.123	.768	.381	.002
	Time × Biodiversity × Sound	.001	1	.001	.007	.931	.000
Depression	Time	.406	1	.406	3.168	.076†	.010
	Time × Biodiversity	.076	1	.076	.595	.441	.002
	Time × Sound	.144	1	.144	1.124	.290	.004
	Time × Biodiversity × Sound	.515	1	.515	4.024	.046**	.013

***Significant at the 1% level, ** Significant at the 5% level, † Marginally significant at the 10% level

3.3.3 The effects of the visual and auditory exposures on psychological responses: ANCOVA (Between subject comparisons)

To examine the effects of biodiversity and the presence of sound on psychological responses among the four groups, we performed 2 × 2 ANCOVA analyses. The level of biodiversity (low vs. high) and the presence of sound (no sound vs. sound) were considered as factors and the restorative state and mood state as dependent variables. The pretest results (T1), not reported in this study, were only used as the covariates in order to control the baseline of the psychological status of respondents.

Table 9 shows that the main effect of sound on the restorative state only approached significance, $F (1,314) = 2.770$, $p = 0.097$, $\eta2 = 0.009$. No sound condition had a higher restorative effect than the environment with a sound condition. No interaction effect was detected between the level of biodiversity and the presence of sound. With respect to tension, a significant effect was confirmed in the interaction between the level of biodiversity and the presence of sound, $F (1,314) = 3.968$, $p < 0.05$, $\eta2 = 0.012$. A lower degree of tension was found in a high biodiversity with sound environment. In terms of fatigue, there was no significant effect on both two factors or interactions. As for depression, there was marginal significant interaction between the level of biodiversity and the presence of sound, $F (1,314) = 3.678$, $p = 0.056$, $\eta2 = 0.012$.

Table 9 Results of ANCOVA models for biodiversity, sound, and the combination effects after intervention (T2)

Variables	Interaction	Sum of squares	df	Mean square	F	p-value	Partial Eta Squared
Restorative state	Baseline (T1)	127.296	1	127.296	493.622	.000***	.611
	Biodiversity	.283	1	.283	1.099	.295	.003
	Sound	.714	1	.714	2.770	.097†	.009
	Biodiversity × Sound	.148	1	.148	.574	.449	.002
Tension	Baseline (T1)	390.357	1	390.357	1674.879	.000***	.842
	Biodiversity	.252	1	.252	1.079	.300	.003
	Sound	.152	1	.152	.652	.420	.002
	Biodiversity × Sound	.925	1	.925	3.968	.047**	.012
Fatigue	Baseline (T1)	404.438	1	404.438	1283.221	.000***	.803
	Biodiversity	.170	1	.170	.538	.464	.002
	Sound	.180	1	.180	.573	.450	.002
	Biodiversity × Sound	.001	1	.001	.004	.952	.000
Depression	Baseline (T1)	434.087	1	434.087	1707.625	.000***	.845
	Biodiversity	.120	1	.120	.471	.493	.001
	Sound	.252	1	.252	.991	.320	.003
	Biodiversity × Sound	.935	1	.935	3.678	.056†	.012

***Significant at the 1% level, ** Significant at the 5% level, † Marginally significant at the 10% level

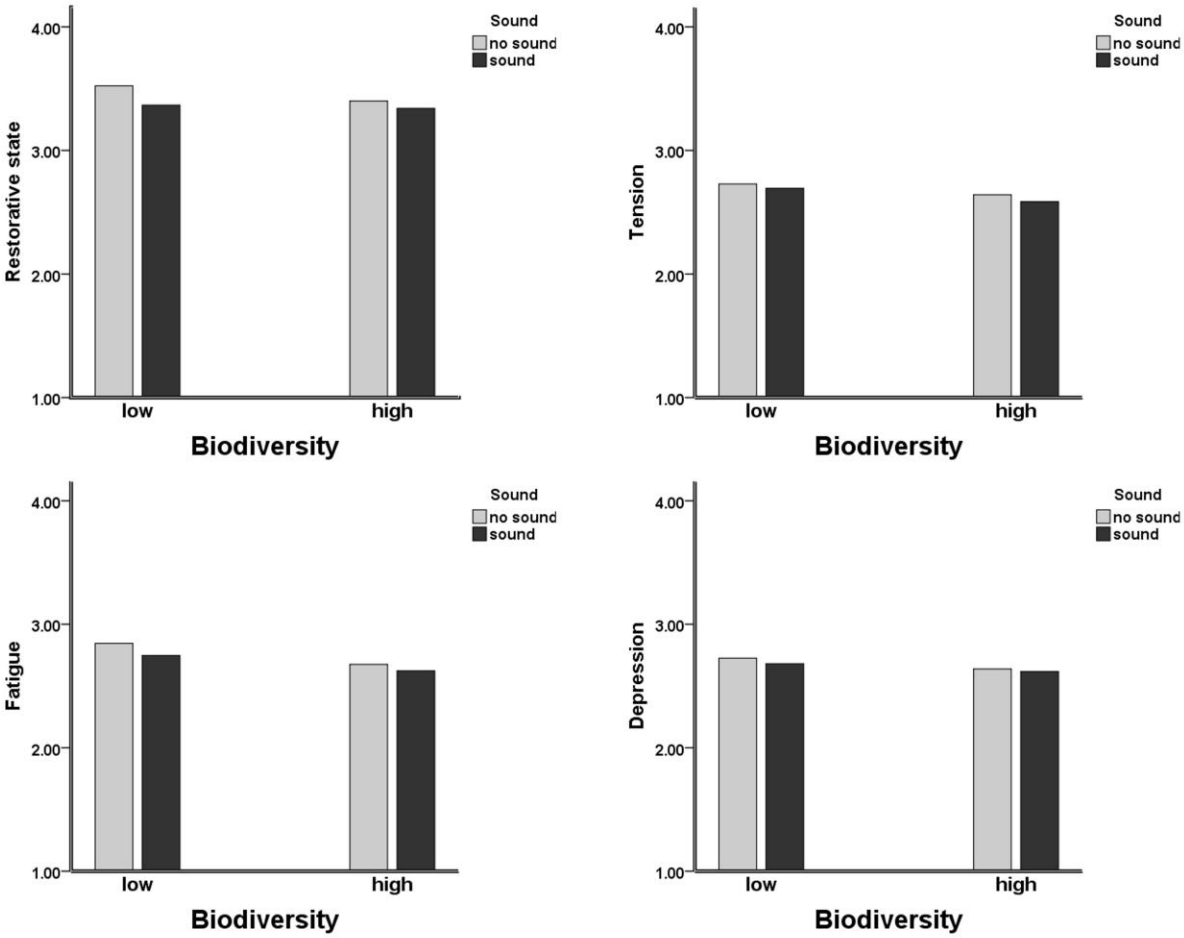


Figure 8 The average scores of restorative and mood states in the four different conditions at post intervention (T2). The lower restorative and negative mood states were found in the environment with high biodiversity and sound conditions.

3.3.4 Perceived species richness

A series of four linear regressions were conducted to examine the associations between perceived species richness and psychological responses. It appears that all four outcomes of psychological responses were positively associated with perceived plant species richness at the 0.001 level of significance ($p<0.000$): restorative states (β=0.226, r^2=0.084); tension (β=0.388, r^2=0.111); fatigue (β=0.408, r^2=0.113); and depression (β=0.390, r^2=0.101).

We performed a one-way ANOVA analysis to examine mean differences of perceived species richness between two pairs of comparison settings—the level of biodiversity (low vs. high) and the presence of sound (no sound vs. sound), with perceived plant species richness as a dependent variable, but there were no statistical differences among them (F (3,311) = 0.286, p = 0.835). Table 10 indicates that the mean value of perceived plant species richness was similar between the four environments.

Table 10 The average scores of perceived species richness in the four environment settings

Variables	Low biodiversity			High biodiversity		
	No sound (n=79)	Sound (n=80)	Total (n=159)	No sound (n=80)	Sound (n=80)	Total (n=160)
Perceived plant species richness	3.04 (1.01)	2.90 (0.98)	2.97 (1.00)	2.91 (1.08)	2.92 (1.07)	2.92 (1.07)

Notes: Values are mean (min: 1; max: 5), with standard deviation inside parentheses;
One way ANOVA results, F (3,311) = 0.286, p = 0.835

3.4 Discussion and Conclusion

The effects of the environmental intervention (treatment) on psychological responses

Environmental stimuli through a 360-degree video can have an impact on subjects' psychological responses. Compared to the baseline mood state at the pretest condition, participants' mood states, such as tension, fatigue, and depression, were significantly lower after viewing the nature scene videos. This finding is consistent with those from previous studies claiming that an indirect experience of nature through a computer display also leads to a restorative effect (Browning et al., 2020; Deng et al., 2020b; Van den Berg et al., 2014; Yu et al., 2018; Zhao et al., 2018). With such a result, it should be noted that online or virtual exposure to simulated green spaces may promote people's mental restoration. Therefore, a wide variety of new possibilities for using online platforms can be suggested in green space and biodiversity research exploring people's psychological well-being. Especially when researchers have been prohibited from in-person (face to face) experiments due to Covid-19, online platforms can be alternatives for mental health studies.

The influences of biodiversity on psychological responses

The results revealed that the main effects of natural sound and the level of biodiversity do not have a statistically significant effect on restorative and mood states. However, the results still show that a lower negative mood state was found in the sound environment. Moreover, a high biodiversity environment did reduce the negative mood state more than a less biodiverse environment (see Figure 8). The findings of our study are consistent with those of previous studies indicating that a high level of biodiversity contributes to positive psychological restoration and wellbeing (Carrus et al., 2015; Fuller et al., 2007; Wolf et al., 2017; Wood et al., 2018). The effect of biodiversity on psychological response might be partly because there is a significant interaction effect between auditory and visual stimuli. The result of this study is in line with previous studies in which there was a significant interaction effect between auditory and visual stimuli on psychological responses (Deng et al., 2020b; Lindquist et al., 2016; Lindquist et al., 2020; Zhao et al., 2018). Such an interaction effect indicates that a single element of visual or auditory stimuli cannot explain a reduction in negative mood state among participants. In this study, we used the natural sounds synchronous with the site when the video was recorded. People tend to be aware of specific landscape components when they hear sounds corresponding to the environment since hearing and vision are closely intertwined (Deng et al., 2020b). At the same time, natural sound also contributes to increasing restorative effects along with visual stimuli (Abbott et al., 2016; Alvarsson et al., 2010; Emfield and Neider, 2014).

The associations between perceived biodiversity and psychological responses

This study also found that respondents who see more perceived species richness are more likely to have higher negative mood states. This is inconsistent with previous findings that perceived biodiversity can lead to psychological benefits (Dallimer et al., 2012; Schebella et al., 2019; Southon et al., 2018). This is partly because people could not accurately perceive site biodiversity. The result of the ANOVA analysis indicates that there was no significant difference in perceived species richness between low- and high- biodiversity environments. As the accuracy of perception of biodiversity is related to respondent's wildlife knowledge and pro-environmental behavior (Dallimer et al., 2012; Southon et al., 2018), our sample group, undergraduate and graduate students in the U.S., might have a lack of knowledge of wildlife, resulting in a mismatch between actual and perceived biodiversity environments. Moreover, Lindquist et al. (2020) found that perceived biodiversity is increased with the presence of sound, however, the results of our study reveal that there is no significant difference in perceived species richness between a sound and a no sound environment. Thus, the failure in identifying species richness could lead to a neutralization of the effects of perceived biodiversity on respondents' mental restoration.

The role of campus landscape biodiversity in the mental restoration of students

The campus landscape of contemporary universities is "park-like," influenced by the European Beaux-Arts tradition. It is the fabric that holds the buildings and facilities together and represents the rational organization of outdoor spaces such as small-to-large mowed lawns, wooded groves, and courtyards and quadrangles (Turner, 1984; Van Yahres and Knight, 1995). In this study, we envision a biodiverse campus landscape as an escape for university students overwhelmed by academic work. Our findings add to the mounting evidence that campus green spaces play a significant role in improving restorative effects for students (Akpinar, 2016; Amicone et al., 2018; Li and Sullivan, 2016; van Dijk-Wesselius et al., 2018). Contrary to our expectation, no single factor, either visual (the level of biodiversity) or aural stimuli (the presence of sound), was able to explain students' mental recovery. In this study, we conclude that there is an interaction between visual and auditory stimuli. This finding highlights the importance of a multisensory approach in mental restoration when students' stress is reduced during their studies. To enhance the mental health of students, campus administrators need to provide more biodiverse green spaces for students not just simply visually appealing greenness. A more biodiverse campus can have a greater restorative effect than a less biodiverse landscape. High species richness in animals and plants leads to soft fascination, resulting in mental restoration. Considering that a large portion of campus landscapes consist of manicured grassland, the provision of such a biodiverse landscape could have a considerable impact on students as a whole. What is more, a biodiverse campus landscape could have a greater restorative potential with natural sounds. As biodiverse landscapes provide more habitats for animal species like birds and insects, songs from those animal species can help offset the exposure to daily noise and contribute to a deeper restoration effect along with the visual stimuli. Landscape planners should consider the creation of biodiverse habitats which could lead to plant and animal species richness, maximizing the combination effect of visual and auditory stimuli from both animal and plant species. A transformation of manicured grass to native meadow gardens or biotope could be an alternative way to increase campus biodiversity when land for green space is limited.

Limitations

Several limitations in this study must be taken into consideration. First, our study was conducted through an online format due to Covid-19, which limits us in conducting an in-person experiment. This could result in minimizing the effects of environmental intervention on research participants since experimental conditions were not fully controlled by the researchers. In addition to this, this study used the 360-degree view video for visual and auditory stimuli to participants. Compared to an on-site experiment, the video is a less effective tool to allow people to immerse themselves in the environment. This can limit one's ability to perceive site biodiversity as simulated environments are not as tangible as the real-world environment and participants cannot get close enough to plant species for observations. To increase environmental exposure and intervention, an on-site field is highly recommended. In relation to this, future research needs to be done on this experiment in a laboratory using virtual reality (VR) devices which creates a more immersive experience and prevents any outdoor disturbances for participants. Second, all psychological response variables relied on self-reported states. Along with subjective measurement, an objective indicator such as physiological responses should be considered in a future study. Third, there was a mismatch between actual and perceived biodiversity among participants. For example, respondents perceived low species richness even when they were assigned to a high biodiversity environment. Therefore, future research should reduce those gaps by controlling visual cues such as the vegetation structure (e.g., the combination and layout of trees, shrubs, and herbaceous plants), height, and color. Last, this study examined the associations between perceived biodiversity and psychological responses. However, we did not attempt to look at the possible mediating effect between perceived biodiversity, actual biodiversity, and psychological responses due to the limitations of our collected data. While actual species richness is a binary variable (low, high biodiversity), perceived species richness and psychological response are continuous variables. Future research should consider the possible mediators between those variables.

Conclusion

In this study, we investigated whether a biodiverse environment could lead to a restorative effect for students with a focus on a multisensory (visual and auditory) approach. A four-group, pre-posttest-randomized experiment design (2×2 factorial design) was conducted to test the restorative effect via the online platform survey. Results showed that, individually, both the visual factor (the level of biodiversity) and auditory factor (the presence of natural sound) did not have statistical significance on mental restoration. However, a significant interaction effect was found between the visual and auditory settings, indicating that a high biodiversity with the presence of natural sound contributed to restorative benefits for students. By considering the result of this study, campus designers and administrators can make better campus environments to enhance the mental wellbeing of students.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Chapter 4 - [2]Urban green space alone is not enough: A landscape analysis linking the spatial distribution of urban green space to mental health in the city of Chicago

4.1 Introduction

According to the U.S. Department of Health and Human Services Substance Abuse and Mental Health Services Administration, approximately one out of five American adults had some kind of mental illness in 2016 (Ahrnsbrak et al., 2017). The Covid-19 pandemic also poses an unexpected threat to mental health (Fiorillo and Gorwood, 2020; Shigemura et al., 2020; Usher et al., 2020). In particular, government actions during a pandemic such as quarantining, social distancing, and self-isolation could be detrimental to mental health (Fiorillo and Gorwood, 2020). Mental health issues can have a great impact on the daily life of individuals, including a loss of productivity, social interactions, and employment (World Health Organization, 2001). In addition, mental health problems result in significant costs not only for individuals but also for governments. Total spending on mental health treatment in the United States increased from $147 billion in 2009 to $239 billion in 2020 (Substance Abuse Mental Health Services Administration, 2014).

It is well known that socio-demographic and environmental factors such as income, education, marital status, race, neighborhood greenness, urban density, and traffic noise affect

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mental health (Businelle et al., 2013; Evans, 2003; Herrera et al., 2018). Among these factors, urban green spaces can be drivers of restorative environments. As humans have an innate affinity for nature (biophilia) (Kellert, 1995), the exposure to urban green space through a wide array of activities plays a significant role in providing psychophysiological benefits for urban populations (Olszewska-Guizzo et al., 2020). Many previous studies have shown that mental health is positively associated with the amount of green space in the urban environment (Beyer et al., 2014; Liu et al., 2019; Mårtensson et al., 2009; Mukherjee et al., 2017; Pun et al., 2018; Sturm and Cohen, 2014; Ward Thompson et al., 2016). In addition, the distance to the nearest green space is a well-known environmental correlate of mental health. Urban residents who live in neighborhoods near green spaces are more likely to have fewer mental health problems than those who live farther away (Coppel and Wüstemann, 2017; Nutsford et al., 2013; Sturm and Cohen, 2014). The mental health benefits of urban green space are also likely to depend on the frequency, duration, and intensity of use (Zhang et al., 2017a).

In this study, we sought to address several questions regarding the relationship between green space and mental health. Is green space alone enough? Are all green spaces the same? Most previous studies on urban green space and mental health regard urban green spaces as homogeneous land covers, generally dichotomized into either natural or impervious areas (Li et al., 2019). In most urban environments, however, the types and composition of urban green spaces (e.g., trees, grass, water bodies) vary widely. Furthermore, the psychological benefits of the spatial configuration (i.e., distribution) of urban green spaces remain insufficiently explored, beyond just the presence or amount of urban green space. In particular, few attempts have been made to investigate the association between mental health and the compositional and configurational aspects of urban green space together. Since the types and distribution of green space contribute to the character of the visual landscape that humans perceive (Chmielewski et al., 2020; Lee et al., 2008) and influence usage patterns of those spaces (Zhang et al., 2017a), studies investigating the relationship between landscape pattern and mental health could help to inform future landscape planning and urban design to enhance these benefits.

The relative effects of urban green space on mental health may be different depending on the type of green space. Among various types of green land-cover types that have been studied (e.g., forest, wetland, agricultural land, rangeland), forested areas were found to have the most significant effect on mental health (Akpinar et al., 2016; Tsai et al., 2018), with increased tree cover associated with fewer mental health problems within urban areas (Chiang et al., 2017; Wu and Jackson, 2017; Yoshida et al., 2015). Tree canopy can contribute to the thermal comfort environment that promotes a greater sense of relaxation and comfort in the urban area (Chiang et al., 2017; Yoshida et al., 2015). In line with these findings, several studies confirmed that psychological restoration can also be achieved through exposure to grass land covers (Nordh et al., 2011; Nordh et al., 2009), water bodies (Dempsey et al., 2018; Nutsford et al., 2016; Völker et al., 2018), and even, farmland (Alcock et al., 2015). It is unclear which types of green space have the greatest effect on the mental health of urban residents in metropolitan areas, however.

A further question we sought to address is whether landscape diversity (landscape heterogeneity) influences the relationship between green space and mental health. The term landscape diversity refers to the number and relative abundance of land covers within the broader landscape (Palmer, 2004; With, 2019). A connection between mental health and landscape diversity is expected for several reasons. Landscape diversity can contribute to a greater visual preference effect (de Val et al., 2006) due to increased scenic complexity and variety (Dronova, 2017; Tabrizian et al., 2020). For example, urban green spaces that contain a diversity of natural elements such as trees, grass, and water bodies can result in higher visual preference and greater restorative effects than natural spaces comprising a single element (de Val et al., 2006; Kuper, 2017; Lindal and Hartig, 2015). From an ecological standpoint, landscape heterogeneity is an indicator of habitat or ecosystem diversity, which in turn may contribute to greater species richness (Dauber et al., 2003; Meyer-Grandbastien et al., 2020; Schindler et al., 2013). A heterogeneous landscape tends to be associated with higher biodiversity by offering a greater variety of habitats or resources that can host more species (Rocchini et al., 2010). As there is growing empirical evidence that biodiversity in urban green spaces is positively associated with psychological restoration and well-being (Carrus et al., 2015; Fuller et al., 2007; Sandifer et al., 2015; Southon et al., 2018), landscape diversity can contribute to improved mental health. Finally, a diverse landscape may contribute to environmental enrichment that satisfies different types of needs, opportunities, and activities that collectively enhance the well-being of urban residents (Beute et al., 2020; Ekkel and de Vries, 2017).

Since urban green spaces are heterogeneous in their composition (With, 2019), it is fair to assume that the spatial distribution (e.g., aggregation, sizes, distance) of urban green spaces varies as well. For example, a given amount of urban green space can be distributed either as “several small spaces” or “a single large space” (Le Texier et al., 2018). Holding the total amount of green space constant, a disaggregated landscape will consist of many small green spaces, whereas an aggregated landscape will have just one or a few large green spaces. It has yet to be clearly determined whether the degree of green space aggregation and its variability is associated with the mental health of urban residents. However, many studies have reported a positive relationship between the size of green space areas and mental health (Akpinar et al., 2016; Nutsford et al., 2013). This is partly because a larger green space with a greater amount of visible space within a view produces a higher restoration effect (Ekkel and de Vries, 2017; Olszewska-Guizzo et al., 2018). Also, users of large green spaces may stay longer and engage in a greater variety of outdoor activities, which can lead to better mental health and well-being (Ayala-Azcárraga et al., 2019; Giles-Corti et al., 2005; van den Berg et al., 2017; Waltham et al., 2014). A large urban park can also be utilized for recreational purposes (e.g., football, running, or walking), resulting in informal interactions between neighbors and stimulating social cohesion that protects against certain mental health risks (Kaźmierczak, 2013; Kingsbury et al., 2020; Peters et al., 2010).

Despite their mental health benefits, large areas of green space are rarely found within densely populated urban centers and the distance necessary to access them can discourage people from using them frequently. Some studies have found that a number of small green spaces distributed throughout the urban area can promote everyday experiences of the outdoors and with better accessibility (Peschardt et al., 2012). Small green spaces, like domestic gardens and roadside trees, can facilitate human-nature interactions in everyday life (Ekkel and de Vries, 2017), and thereby lead to mental restoration and well-being (Peschardt et al., 2012). Such cumulative short but frequent contacts with nature can also promote social interactions and cohesion among people in their neighborhoods (de Vries et al., 2013; Kingsley and Townsend, 2006), since green spaces are attractive places where people tend to congregate or engage in activities like recreational walking, which can facilitate contact between neighbors (Ekkel and de Vries, 2017).

The connectivity of urban green space also contributes psychological benefits. The early idea of the “Emerald Necklace” by Frederick Law Olmsted in Boston is that a network of parks linked by green corridors and parkways can offer both social and ecological benefits (e.g., increased social interactions, increased species diversity, potential for flood-risk mitigation) to people within an urban landscape (Mell, 2008). Well-connected natural spaces could provide people with more opportunities to access biodiverse environments and thus enhance their overall satisfaction with their neighborhoods (Park, 2017). Moreover, green corridors can promote a reduction in stress and negative mood states (Marselle et al., 2013) and support psychological well-being (Marselle et al., 2015). High connectivity among green spaces also encourages incidental users such as cyclists and runners to spend more time in green space (Dong et al., 2020).

4.1.1 Research aims and questions

A small but growing number of studies have attempted to investigate the role of landscape pattern (both composition and configuration) on various psychological aspects, such as visual preferences (de Val et al., 2006; Palmer, 2004), neighborhood satisfaction (Lee et al., 2008), and mental health (Akpinar, 2015; Chou et al., 2016; Tsai et al., 2018). To our knowledge, no previous studies have investigated the relationship between mental health and the composition and configuration of urban spaces within a large metropolitan area having a population of more than 1.5 million (OECD, 2020), such as our focus here on the city of Chicago in the United States. People living in large cities are at a higher risk for poor mental health owing to increased air pollution, traffic, noise, and physical threats from accidents and crime that can have adverse psychological effects on residents (Gruebner et al., 2017). In the city of Chicago, 4.8% of the population reported experiencing serious psychological distress and 34.7% of the youth population suffered from depression in 2017, according to the Healthy Chicago 2.0 Survey (The Chicago Department of Public Health, 2017a).

Our goal is thus to examine whether certain landscape metrics of urban green space that describe the composition and configuration of each type of green space (trees, grass, water) as well as all green space combined, are associated with the level of psychological distress reported by individuals in Chicago. In terms of the expected relationships based on previous studies, we hypothesized that:

1) the amount of tree cover within the urban landscape will have the strongest correlation with mental health, irrespective of other green cover types;
2) a greater diversity of green-space types within the urban landscape (Figure 9a) will be associated with better mental health (as reflected in lower psychological distress scores);
3) better mental health will be reported in urban landscapes having large, connected, and/or aggregated green spaces of any type (tree, grass, or water); and,
4) better mental health will occur within urban landscapes having large amounts of total green space (tree, grass, and water combined), or those in which green spaces are connected and/or exhibit an aggregated distribution (Figure 9b).

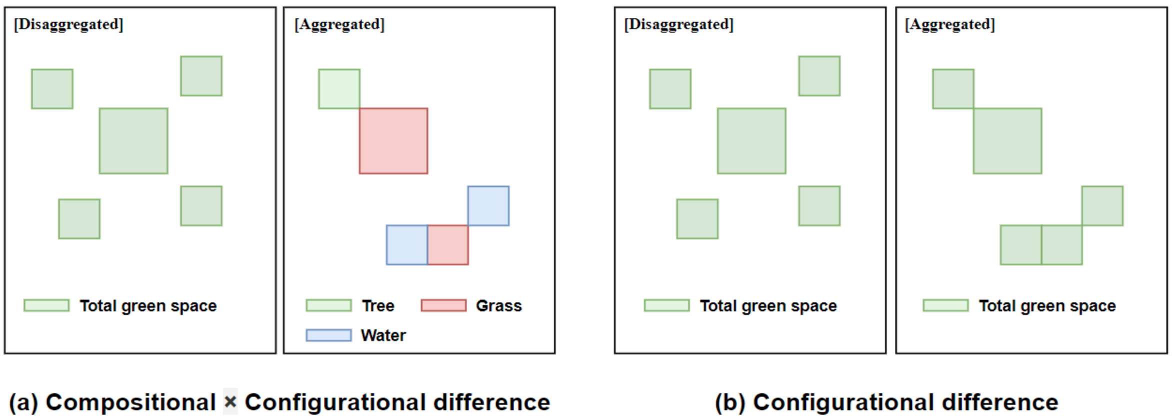

Figure 9 Given the same amount of urban green space, there is the potential for both compositional and configurational differences in the distribution of that green space within the urban landscape

4.2 Methods

4.2.1 Study area and population

We conducted a cross-sectional study to determine the association between landscape pattern and the psychological distress levels of urban residents in the city of Chicago. We focused on Chicago for several reasons. First, the city of Chicago is the third largest in the United States with 2.7 million inhabitants within the city limits (U.S. Census Bureau, 2020). Second, Chicago has had a comprehensive zoning ordinance in place since 1923, providing us with a variety of urban landscapes that vary in their relative amount of developed areas (commercial, manufacturing, residential) for analysis (Zhou et al., 2008). Third, Chicago is rich in urban green spaces that vary from small amenity urban parks (e.g., Union Park) to large natural areas (e.g., Sidney Yates Flatwoods) that have been designed or protected for the benefit of Chicago residents. Finally, and most critically, we were able to obtain mental health data for this metropolitan area.

The mental health data used in our study were collected from 2015 to 2017 by the Chicago Department of Public Health for their Healthy Chicago Survey (HCS). The HCS is a pooled time-series of cross-sectional data that surveyed the mental and physical status of a total of 8,442 people in 77 Chicago community areas; that is, 8,442 respondents (individual level) are nested within 77 community areas (group level). The 77 community areas were defined by Chicago sociologists with a focus on geographic, social, and cultural factors (Whitman et al., 2004). Samples were collected from landline and cellular telephones using random sampling methods. The questionnaire also included questions about socioeconomic status (SES) such as gender, race, age, income, body mass index (BMI), and general health. The eligibility of respondents was limited to individuals older than 18 years of age, who were Chicago residents, and lived in privately-owned residences. In our analysis, respondents from 16 community areas were excluded due to small sample sizes. After excluding any missing and unanswered data, the dataset provided us with a total of 6,405 individuals from 61 community areas that we included in our subsequent analyses.

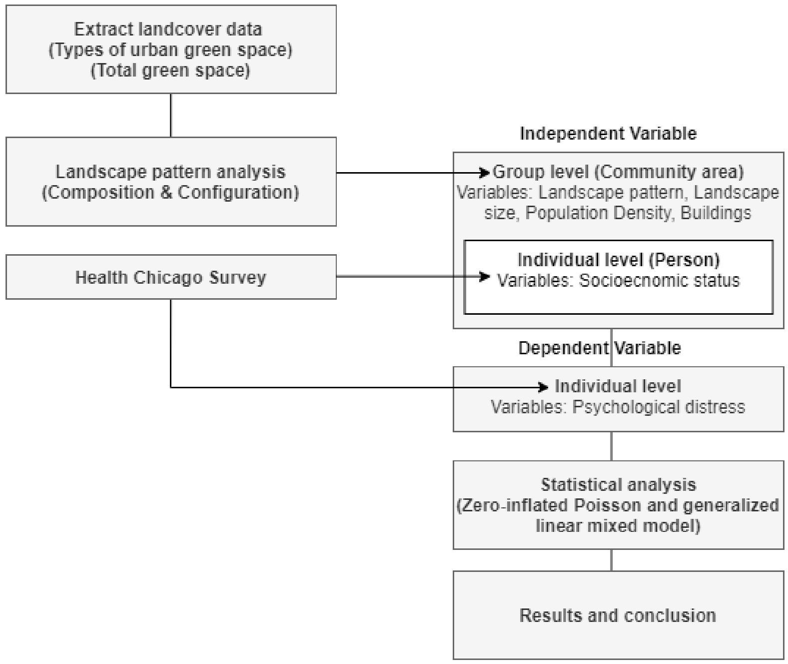

Figure 10 The flow of the analysis

4.2.2 Individual-level predictors

Outcome variables: Psychological distress

The HCS uses the Kessler 6 Psychological Distress Scale, in which individuals are asked to rank the frequency with which they had experienced each of the following six emotional states over the past year 30 days: “nervous,” “hopeless,” “restless or fidgety,” “depressed,” “everything was an effort,” and “worthless” (Kessler et al., 2003; Kessler et al., 2010). Responses are rated on a 5-point Likert scale in which a score of 0 indicates that the individual experienced that particular emotional state “none of the time” and a score of 4 represents “all of the time.” Psychological distress is thus a composite score (Kessler 6 or K6) obtained as the sum of the ranked responses to each question, and ranges from 0 (no psychological distress) to 24 (high psychological distress).

Confounding variables: SES, neighborhood safety, and belonging

Many health-related studies have shown that there is a strong association between SES and mental health, as an individual's socioeconomic circumstances may strongly determine one's mental health (Akpinar et al., 2016; Fan et al., 2011; Larson et al., 2018; Ward Thompson et al., 2016). We therefore included gender, ethnicity, education, age, income, general health, and BMI as confounding variables in our analysis. We also included two other confounding variables in our analyses, the perception of neighborhood safety and belonging, because both have been shown to play a pivotal role in social cohesion that can reduce mental health risks (Kloos and Townley, 2011; Wang et al., 2019c). The perception of neighborhood safety was rated in a questionnaire by Aminzadeh et al. (2013): "Do you feel safe in your neighborhood?" (1=Yes, all of the time; 2=Yes, most of the time; 3=Sometimes; 4=No, mostly not). Neighborhood belonging was assessed by the answer to the question: "I really feel part of my neighborhood" (1=Strongly agree or agree; 2=Neither agree nor disagree; 3=Disagree or strongly disagree).

4.2.3 Group-level predictors

Explanatory variables: Landscape metrics

We obtained High-Resolution Land Cover (HRLC) data for the city of Chicago, for our analysis of urban landscapes (Chicago Metropolitan Agency for Planning, 2010). The HRLC is a raster dataset with a 1-m resolution. The original sources of the HRLC were obtained from 2008 LiDAR data and 2010 NAIP imagery. Based on an analysis of land-cover change by the USGS National Land Cover Database (the Land Cover Change Index for the CONterminous United

States, CONUS), there has been only a 0.63% change in urban green space in the city of Chicago between 2001 and 2016, when the HRLC and HCS data were collected, respectively (Homer et al., 2020)). Land covers in the HRLC are classified into seven types: tree canopy, grass/shrub, bare earth, water, buildings, roads, and other paved surfaces (Figure 11). We considered tree canopy, grass/shrub, and water to be separate categories of urban green space in this study.

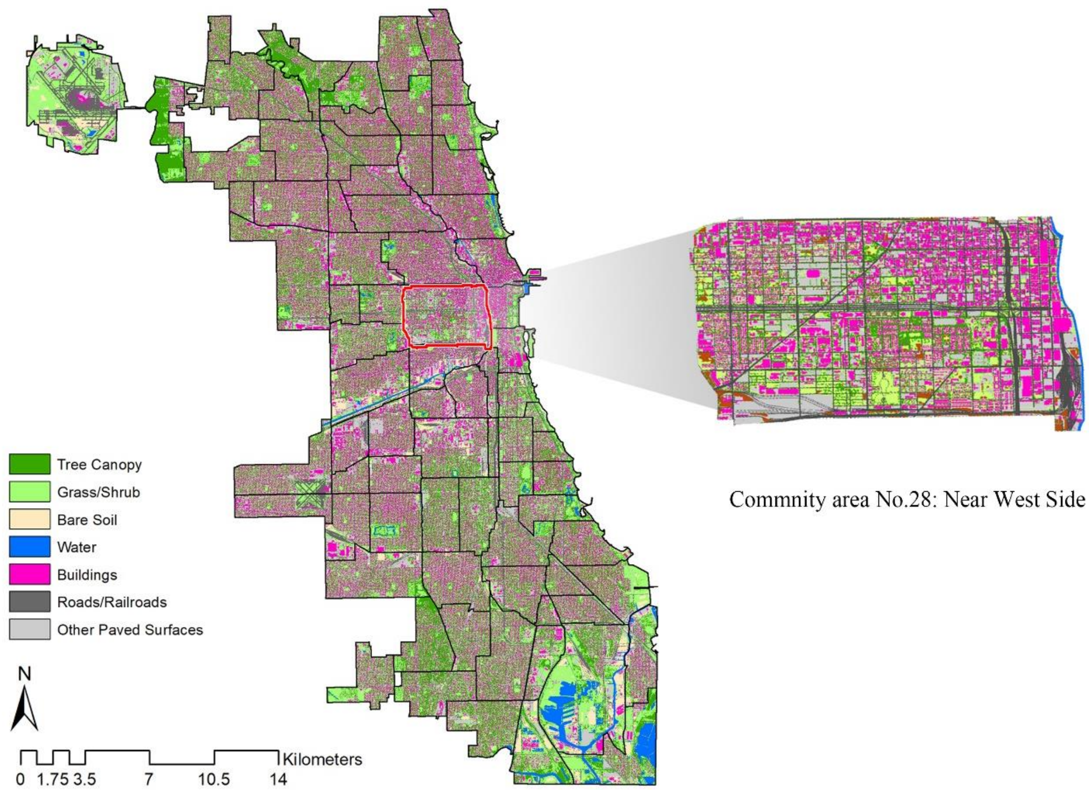

Figure 11 Land-cover classification within designated community areas (urban landscapes) in the city of Chicago

We quantified the amount and configuration of each green-space type, as well as all types combined (total green space), within the each community areas. For each of the 61 community areas ('landscapes'), we calculated a number of landscape metrics using FRAGSTATS v4.2 (McGarigal et al., 2012). Landscape composition was assessed by two metrics. First, the proportion of each type of urban green space was measured as a percentage of the total landscape (PLAND). PLAND is the most basic measure of landscape composition, and explains the relative abundance of each land-cover type (McGarigal, 2015). Second, the diversity of urban green-space types within a landscape (landscape diversity) was captured by the Shannon's diversity index (SHDI), which quantifies both the richness and relative abundance of different land-cover types (McGarigal, 2015; With, 2019). A landscape with many land-cover types (high richness) that all have the same relative abundance (high evenness) would be considered to have high landscape diversity (higher SHDI values). Higher SHDI values represent more heterogeneous and complex views (Meyer-Grandbastien et al., 2020; Tabrizian et al., 2020) and may be associated with more biodiverse environments (Rocchini et al., 2010).

Since many landscape configuration metrics describe the properties of "patches," it is necessary to first define how cells (pixels) of a given land-cover type are to be joined within the analysis. In our landscape analysis here, we applied the 8-cell neighborhood rule, in which cells of a given type are considered part of the same patch if they share an edge or corner. We then evaluated three metrics of landscape configuration. First, we quantified the relative size of green spaces in these urban landscapes by obtaining the area-weighted mean patch size (AM) for each type of green space and for all green spaces combined. The area-weighted mean gives greater weight to larger patches and thus provides a more representative measure of average patch size than the arithmetic mean (which is heavily influenced by small patches; (With, 2019)). Higher AM values indicate larger urban green spaces for a given type.

Second, we measured the degree of aggregation of each green-space type, as well as the total green space, using the clumpiness index (CI). The value of CI is close to 1 when the corresponding patch type is fully clumped, close to -1 when the corresponding patch type is fully disaggregated (every cell is a separate patch), and is equal to 0 when the corresponding patch type is randomly distributed (Botequilha Leitão and Ahern, 2002; McGarigal, 2015; With, 2019). Within the context of urban landscapes, a disaggregated landscape pattern would have a large number of small green spaces (CI < 0), whereas a clumped landscape would have a small number of large green spaces (CI $\rightarrow$1). Among the many metrics available for calculating landscape aggregation, CI is preferred because it is less influenced by the amount of a given land cover (Neel et al., 2004; With, 2019).

Lastly, we assessed landscape connectivity to determine whether the apparent accessibility of urban green space (of a given type or all types combined) has a positive association with mental health. Previous health-related studies have measured landscape connectivity using a patch cohesion index (COHESION) (Akpinar, 2015; Lee et al., 2008; Tsai et al., 2018). COHESION calculates the physical connectedness of given patch types and contains information on patch area and patch perimeter. Though COHESION has been widely used to examine landscape connectivity, the COHESION index is confounded with several other landscape metrics (McGarigal, 2015). A simpler measure of landscape connectivity can be obtained using the Mean Nearest-Neighborhood Distance (MNN) among patches (green spaces) of a given type, and well as to green spaces of any type (Chardon et al., 2003; Magle et al., 2009). Compared to COHESION, MNN has two benefits in that it is easy to compute and interpret (With, 2019). Lower values of MNN indicate greater potential accessibility of the corresponding green-space type.

Table 11 Landscape metrics used to define the composition and configuration of green space within urban landscapes of Chicago

Landscape metrics	Description	Unit
Percentage of green space (PLAND)	Percentage of landscape comprising either tree cover, grass cover, or water cover (e.g., $PLAND_{tree}$)	%
Landscape heterogeneity (Shannon's diversity index, SHDI)	The richness and relative abundance of different urban green spaces across the entire landscape	> 0
Mean Nearest-Neighborhood Distance (MNN)	The average distance to the nearest patch of the same type, calculated separately for tree cover, grass cover, and water bodies (e.g., MNN_{tree})	m
Clumpiness Index (CI)	A measure of aggregation based on the likelihood that two cells of the same type (tree, grass, water) are adjacent (e.g., CI_{tree})	-1 - 1
Area-weighted mean patch size (AM)	The area-weighted mean patch size for each type of green space, calculated separately for tree cover, grass cover, and water bodies (e.g., AM_{tree})	m^2
Mean Nearest-Neighborhood Distance of total green space (MNN_{total})	The average distance to the nearest patch of any type of green space (tree, grass, or water)	m
Clumpiness Index of total green space (CI_{total})	A measure of aggregation based on the likelihood that two cells of any green-space type (tree, grass, or water) are adjacent	-1 - 1
Area-weighted mean of total green space (AM_{total})	The area-weighted mean size of patches made up of any type of green space (tree, grass, or water)	m^2
Percentage of total green space ($PLAND_{total}$)	Percentage of total green space	%
Landscape area	The size of each community area	km^2

Confounding variables: Built-environment variables

We also included several community-level factors that could have an impact on mental health outcomes: the building footprint area, the proportion of road/railroad coverage, landscape area, and population density. These measures were obtained from an analysis of HRLC data derived from the GIS calculation. Mental health is known to be directly and indirectly influenced by the urban built environment (Evans, 2003). For example, living in areas of high road density or near busy trafficways can negatively impact the mental health of residents owing to the increased traffic and noise (Bluhm et al., 2004; Dzhambov et al., 2017; Sygna et al., 2014). Simlarly, people who live in densely-populated neighborhoods are more likely to report mental health problems than those living in low-density neighborhoods (Chen et al., 2015; Wang et al., 2020; Williams, 1994).

4.2.4 Statistical analysis

We performed a series of multivariate analyses to examine the relationship between the composition and configuration of urban green space and the mental health of Chicago residents (see figure 9). We used a zero-inflated Poisson and generalized linear mixed models (GLMMs) in order to overcome the following challenges. First, the data were structured hierarchically because individual-level variables (6,405 participants) were nested within the group-level variables (61 community areas). Second, the dependent variable (psychological distress) showed a highly negatively skewed distribution (i.e., our data contained an excess of zero counts). We therefore employed a zero-inflated Poisson model, which uses both a Poisson count model and a logit model to predict excess zeros in our data (Palese et al., 2020). A series of zero-inflated Poisson GLMMs (described in greater detail below) were performed using the R package 'glmmTMB' in RStudio 1.2.1335 (Brooks et al., 2017). All landscape metrics and built-environment variables were standardized (i.e., mean = 0, with unit variance) prior to analysis in order to minimize issues of multicollinearity and unit scale between variables, but we also tested for multicollinearity as explained below.

Our statistical modeling approach is derived from the following equations used by Li et al. (2021) and Chien and Wu (2020). Equation (1) represents the Poisson distribution in the non-structural zero (NSZ) model and equation (2) specifies this model. Equations (3) and (4) explain the zero-inflation model. All notations are as follows: P_{ij} is the probability of psychological distress for individual *i* at *j* community area; λ_{ij} is the expected value of P_{ij}; γ_{00} is the overall mean intercept; γ_k is the k^{th} slope of fixed effects in the Poisson model; *k* refers to the total number of independent variables; X_{ijk} presents to the k^{th} independent variable; $p_{ij}^{(zi)}$ is the zero-inflated probability of individual *i* over different community areas; $\gamma_{00}^{(zi)}$ is the intercept and $\gamma_{t}^{(zi)}$ is the t^{th} slope of the independent variable in the zero-inflated model; t refers to the total number of independent variables; υ_{0j} is the between-community area variance; and, ε_{ij} is the within-community area variance.

$$P_{ij}|NSZ \sim Poisson\ (\lambda_{ij}) \text{ -- } (1)$$

$$\text{Log } (P_{ij}|NSZ) = \gamma_{00} + \sum_{k=1}^{K} \gamma_k X_{ijk} + \upsilon_{0j} + \varepsilon_{ij} \text{ -- } (2)$$

$$p_{ij}^{(zi)} = 1 - \text{Pr (NSZ)} \text{ -- } (3)$$

$$\text{Log}\left(\frac{P_{ij}^{(zi)}}{1-p_{ij}^{(zi)}}\right) = \gamma_{00}^{(zi)} + \sum_{t=1}^{T} \gamma_t^{(zi)} X_{ijt} + \upsilon_{0j} + \varepsilon_{ij} \text{ -- } (4)$$

We tested and compared four models to evaluate our main hypotheses regarding the effect of landscape pattern on mental health. Model 1 was the null model (base model) which only predicted the intercept of the fixed effects, identifying whether or not group-level variables influenced the intercept of the dependent variable (Garson, 2019). Model 2 included a fixed predictor at the individual level. We tested SES variables, including gender, ethnicity, education, age, income, general health, BMI, neighborhood safety, and neighborhood belonging. Models 3 and 4 contained individual and group levels as fixed predictors. Model 3 examined the relationship between landscape patterns of each type of green space at the group level, and psychological distress while controlling SES at the individual level. Model 4 investigated the association between landscape patterns of total green space and psychological distress, controlling for SES. All four specified model equations (Models 1 to 4) are described fully in the supplementary material.

Prior to the analysis of GLMMs, all explanatory variables at the individual and group level were tested for multicollinearity. One member of a pair of explanatory variables with an absolute Pearson correlation coefficient of 0.7 was excluded. We therefore ended up excluding the following variables from further analysis: $PLAND_{water}$, AM_{grass}, CI_{trees}, and $PLAND_{total}$. Following the analysis of our GLMMs, we also evaluated the variance inflation factor (VIF) using the R package 'Performance', which was developed for Zero-Inflated Mixed Models to examine multicollinearity (Lüdecke et al., 2019). Explanatory variables with a VIF >10 were dropped from subsequent analysis, which were CI_{trees}, CI_{grass}, and proportion of road/railroads.

4.3 Results

4.3.1 Descriptive statistics

On average, mental health scores from the HCS suggest that most respondents were experiencing little psychological distress at the time of the survey (mean composite Kessler 6 score = 3.75 $\pm$ 3.96 SD, out of a maximum 24; Table 12). More female respondents participated in the survey than male respondents. Most of the respondents self-identified as either white or black in about equal numbers. Nearly half of respondents had at least a college-level education. More than half of respondents were over 45 years of age. About 40% of participants were categorized at the 400% poverty level, based on the following 2018 federal income-level guidelines for a family of three: 100%: $20,780; 200%: $41,560; 300%: $62,340; and, 400%: $83,120 (FAMILIES USA, 2018). The vast majority of respondents (80%) rated their general health as "good" or "better". However, more than one-third of people were categorized as “obese” and another third were “overweight” based on their BMI. Most respondents perceived their neighborhoods as safe and agreed that they felt part of their neighborhood.

Table 12 Mental health and socioeconomic status of respondents participating in the Healthy Chicago Survey conducted by the Chicago Department of Public Health in 2015-2017

Variable	Frequency	Percentage	Mean (SD)
Gender			
Male	2,746	42.9	
Female	3,659	57.1	
Race			
White	2,394	37.4	
Black	2,489	38.9	
Asian	218	3.4	
Other	158	2.5	
Hispanic	1,146	17.9	
Education			
High school or below	1,815	28.3	
Some college	1,622	25.3	
College or above	2,968	46.3	
Age			
18-29	906	14.1	
30-44	1,819	28.4	
45-64	2,302	35.9	
65+	1,378	21.5	
Poverty Level			
<100%	1,445	22.6	
100-199%	1,199	18.7	
200-399%	1,046	16.3	
400% or greater	2,715	42.4	
General health			
Excellent	1,225	19.1	
Very Good	1,966	30.7	
Good	1,982	30.9	

Variable	Frequency	Percentage	Mean (SD)
Fair	994	15.5	
Poor	238	3.7	
Body Mass Index (BMI)			
Obese (BMI>30)	2,080	32.5	
Overweight (25≤BMI<30)	2,152	33.6	
Normal or Underweight (BMI<25)	2,173	33.9	
Neighborhood safety			
Good	4,924	76.9	
Fair	1,041	16.3	
Poor	440	6.9	
Neighborhood belonging			
Agree	4,171	65.1	
Disagree	2,234	34.9	
Total	**6,405**	**100.0**	

Urban landscapes in the city of Chicago comprised approximately equal amounts of grass and tree cover, which together averaged about 40% of the landscape (Table 13). It is important to note that the minimum percentage of water cover was 0%, indicating that no water bodies were present in some community areas. Nevertheless, the size of water bodies (patches) tended to be larger and more isolated (greater MNN distances) than those of tree and grass covers.

Table 13 Descriptive statistics resulting from a landscape pattern analysis of green space within urban landscapes (n = 61 community areas) of Chicago.

Land cover	Variable (landscape metric)	Mean	SD	Minimum	Maximum
	$PLAND_{trees}$	19.59	7.65	6.91	48.72
	$PLAND_{grass}$	22.45	5.18	12.06	36.52
	$PLAND_{water}$	1.16	2.59	0.00	17.45
	SHDI	0.75	0.10	0.61	1.05

Land cover	Variable (landscape metric)	Mean	SD	Minimum	Maximum
Trees	MNN_{trees}	5.97	0.69	4.41	7.60
	AM_{trees}	2.05	8.00	0.08	59.10
	CI_{trees}	0.85	0.02	0.81	0.91
Grass / shrub	MNN_{grass}	4.31	0.64	3.28	6.24
	AM_{grass}	2.38	6.50	0.13	42.09
	CI_{grass}	0.75	0.04	0.66	0.91
Water	MNN_{water}	88.01	207.51	0.00	1,162.45
	AM_{water}	4.02	19.09	0.00	149.72
	CI_{water}	0.79	0.36	0.00	0.99
Total green space	MNN_{total}	4.30	0.68	3.12	6.43
	AM_{total}	25.79	44.83	1.42	273.78
	CI_{total}	0.89	0.02	0.85	0.96
	$PLAND_{total}$	0.45	0.11	0.20	0.78
Landscape size	Community size (km^2)	8.17	3.93	2.70	28.20

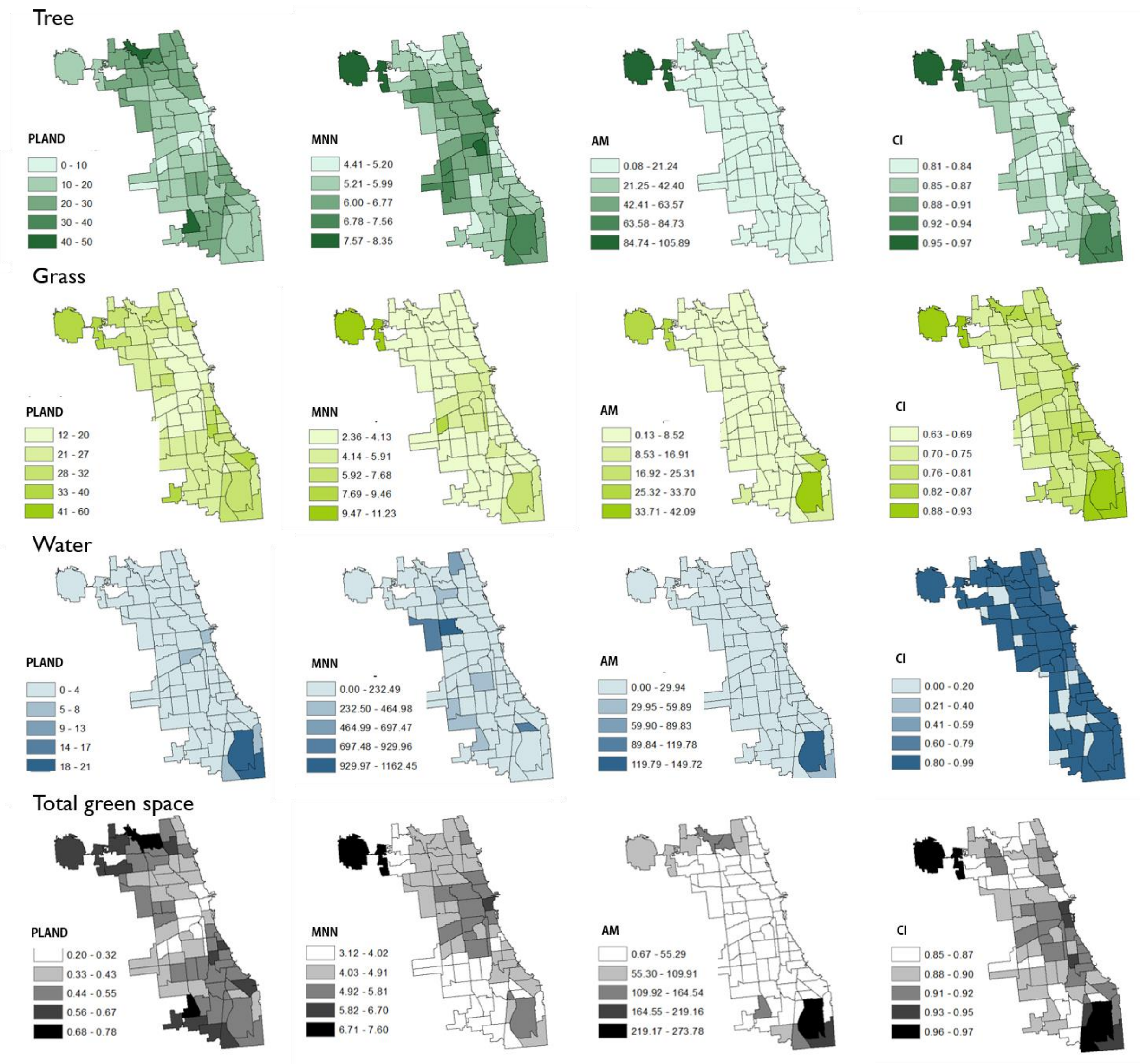

Figure 12 Distribution of landscape metric values across the city of Chicago for individual green-space types (tree, grass, water) and for all green space combined (total green space)

The proportion of each type of built environment varied across community areas. The mean area of the building footprint was 21.83 km^2 (minimum=5.68 km^2, maximum=33.15 km^2, SD=5.59 km^2). The mean area of roads/railroads was 25.06km^2 (minimum=7.91 km^2, maximum=33.15 km^2, SD=11.95 km^2). The mean of population density was 5,943.23

people/km^2 (minimum=441.68 people/km^2, maximum=14,609.69 people/km^2, SD=2.899.92 people/km^2).

4.3.2 Model results

The computed intraclass correlation coefficient (ICC) was approximately 0.06, indicating that 6% of the variance in psychological distress can be explained by the group-level effect of the community area. The null model (Model 1) showed that there was a significant group-level effect, which justifies using mixed-effect models. Model 2 included all individual-level independent variables as fixed predictors (Table 14). In the conditional model results for Model 2 (Table 14), females were at a significantly lower risk of reporting psychological distress relative to males. White residents were more likely to report psychological distress compared to residents of other ethnicities. Highly educated and elderly people were less likely to report psychological distress than those who were not. Compared with respondents who reported poor general health, those who had better general health tended to have no psychological distress. Surprisingly, individuals with a lower BMI had an increased risk of psychological distress than those with a higher BMI. Respondents with a higher level of perceived neighborhood safety were less likely to report psychological distress than those who felt less safe in the neighborhood. Individuals who felt part of their neighborhood were unlikely to report psychological distress.

The regression coefficient of a pair of independent variables in the zero-inflated and conditional models are expected to have an opposite direction (Fan and Habibov, 2009). For example, the count model predicted the presence of psychological distress, indicating that the positive regression coefficient was positively associated with having psychological distress. On the other hand, the zero-inflated model estimated the probability of no psychological distress, and the positive regression coefficient indicated a high probability of having no psychological distress. In Model 2, the coefficient of all SES variables had a negative direction in the conditional model, while a positive coefficient was found in the zero-inflated model.

Model 3 added group-level variables as fixed predictors to Model 2. In this model, we tested the effect of the landscape pattern for each type of green space on psychological distress, while controlling for the individual-level SES variables. In the conditional model results for Model 3 (Table 14), respondents in community areas with high population density were more likely to report higher levels of psychological distress. In the zero-inflated model, respondents in urban landscapes (community areas) having smaller water bodies (AM_{water}) or a greater distance between treed areas (MNN_{trees}) reported lower psychological distress.

Lastly, Model 4 examined the relationship between landscape patterns of total green space and psychological distress using individual- and group-level variables. In the conditional model, the clumpiness index of total green space (CI_{total}) was positively associated with psychological distress. This indicates that the more clumped the green space, the higher the psychological distress reported. As expected, high urban population density was also related to high psychological distress among residents. In the zero-inflated model, however, no statistically significant predictors were found.

Table 14 Generalized Linear Mixed Model for illuminating the relationship between landscape metrics and psychological distress

		Model 1				Model 2				Model 3				Model 4			
		Conditional model		**Zero inflated model**		**Conditional model**		**Zero inflated model**		**Conditional model**		**Zero-inflated model**		**Conditional model**		**Zero-inflated model**	
	Predictors	*Est*	*Z value*	*Est*	*Z value*	*Est*	*Z value*	*Est*	*Z value*	*Est*	*Z value*	*Est*	*Z value*	*Est*	*Z value*	*Est*	*Z value*
Individual level predictors	(Intercept)	1.577	81.36***	-1.21777	-30.19***	1.876	34.250***	-1.673	-6.432***	1.835	4.517***	-3.697	-2.772**	0.419	0.682	1.422	0.677
	Gender																
	Male (ref)																
	Female					-0.034	-2.490*	-0.051	-0.762	-0.033	-2.392*	-0.054	-0.806	-0.033	-2.404*	-0.053	-0.796
	Race																
	White (ref)																
	Black					-0.126	-5.820***	0.732	8.000***	-0.121	-5.458***	0.718	7.438***	-0.117	-5.447***	0.702	7.366***
	Asian					-0.179	-4.220***	0.807	4.370***	-0.181	-4.285***	0.820	4.443***	-0.182	-4.304***	0.814	4.404***
	Other					-0.045	-1.000	0.926	4.643***	-0.046	-1.015	0.927	4.633***	-0.042	-0.930	0.903	4.515***
	Hispanic					-0.208	-8.860***	0.714	6.329***	-0.209	-8.881***	0.674	5.931***	-0.204	-8.725***	0.698	6.164***
	Education					-0.042	-5.730***	-0.059	-1.614	-0.042	-5.764***	-0.050	-1.377	-0.043	-5.824***	-0.054	-1.485
	Age					-0.007	-15.590***	0.025	11.966***	-0.007	-15.592***	0.025	12.159***	-0.007	-15.619***	0.025	11.999***
	Income					-0.063	-16.270***	0.047	2.602**	-0.063	-16.344***	0.048	2.667**	-0.064	-16.427***	0.048	2.636**
	General health					0.169	24.530***	-0.361	-10.398***	0.168	24.475***	-0.366	-10.566***	0.168	24.534***	-0.362	-10.430***
	BMI																
	Obese (ref)																
	Overweight					-0.022	-1.290	-0.094	-1.165	-0.022	-1.300	-0.095	-1.174	-0.022	-1.320	-0.093	-1.158
	Normal/Underweight					0.045	2.680**	-0.245	-2.906**	0.044	2.601**	-0.234	-2.781**	0.043	2.585**	-0.240	-2.848**
	Safety																
	Good (ref)																
	Fair					0.066	3.690***	-0.281	-2.869**	0.066	3.690***	-0.298	-3.045**	0.068	3.765***	-0.288	-2.935**
	Poor					0.272	11.850***	-0.416	-2.763**	0.275	11.951***	-0.430	-2.855**	0.275	11.967***	-0.425	-2.818**
	Belong																
	Agree (ref)																
	Disagree					0.109	7.660***	-0.300	-3.986***	0.108	7.567***	-0.300	-3.996***	0.109	7.626***	-0.300	-3.980***
Group level predictors	$PLAND_{trees}$									-0.031	-0.342	0.168	0.568				
	$PLAND_{grass}$									-0.004	-0.045	0.185	0.720				
	MNN_{trees}									0.075	0.285	2.345	2.792**				
	MNN_{grass}									-0.018	-0.117	-0.268	-0.542				
	MNN_{water}									0.011	0.680	0.061	1.337				
	AM_{trees}									-0.008	-0.489	0.026	0.479				
	AM_{water}									0.025	1.757	-0.108	-2.322*				
	CI_{water}									0.050	1.312	-0.044	-0.382				
	SHDI									-0.026	-0.173	-0.149	-0.322				
	Buildings									-0.003	-0.661	-0.027	-1.613	.			
	Density									0.132	2.193*	0.227	1.243	0.123	3.018**	-0.072	-0.542
	Community size									-0.041	-1.004	0.183	1.549	0.012	0.364	0.198	1.862
	AM_{total}													0.008	0.610	-0.024	-0.516
	CI_{total}													1.345	2.041*	-3.221	-1.442

	Model 1				Model 2				Model 3				Model 4			
	Conditional model		**Zero inflated model**		**Conditional model**		**Zero inflated model**		**Conditional model**		**Zero-inflated model**		**Conditional model**		**Zero-inflated model**	
Predictors	*Est*	*Z value*	*Est*	*Z value*	*Est*	*Z value*	*Est*	*Z value*	*Est*	*Z value*	*Est*	*Z value*	*Est*	*Z value*	*Est*	*Z value*
MNN_{total}													-0.005	-0.046	0.014	0.037
	Random Effects				**Random Effects**				**Random Effects**				**Random Effects**			
	σ^2		0.29		σ^2		0.27		σ^2		0.26		σ^2		0.26	
	τ_{00}		0.02		τ_{00}		0.01		τ_{00}		< 0.01		τ_{00}		< 0.01	
	ICC		0.06		ICC		0.03		ICC		0.01		ICC		0.02	
	N		61		N		61		N		61		N		61	
	Observations		6405		Observations		6405		Observations		6405		Observations		6405	
	Marginal R^2		-		Marginal R^2		0.266		Marginal R^2		0.267		Marginal R^2		0.265	
	Conditional R^2		0.063		Conditional R^2		0.285		Conditional R^2		0.278		Conditional R^2		0.277	

Note: MNN (Mean nearest-neighborhood distance), CI (Clumpiness index), SHDI (Shannon's diversity index), σ^2 (Residual variance of random effects), τ_{00} (Total variance between groups), ICC (Intraclass correlation), N (The number of groups), Marginal R^2 (Variance explained by fixed factors), Conditional R^2 (Variance explained by both random and fixed factors), *** Significant at the 0.1% level, ** Significant at the 1% level, * Significant at the 5% level.

4.4 Discussion

The purpose of this study was to investigate the association between landscape patterns and psychological distress in 61 community areas within the city of Chicago while controlling individual factors (SES, neighborhood safety, and belonging). Surprisingly, there was no relationship between the landscape proportions of different urban green-space types and mental health, as indexed by the Healthy Chicago 2.0 Survey (table 14). This is inconsistent with previous findings in which the percentage of treed (forest), grass, or water cover types was positively associated with mental health (Akpinar et al., 2016; Nordh et al., 2011; Völker et al., 2018). It may be that the relative proportion of each type of green space across the broader landscape is less important to the mental well-being of urban residents than the everyday encounters individuals have with green spaces at a more local scale. For example, individuals may see street trees within their neighborhoods on a daily basis; grassy areas in a small urban park or private garden may provide local spaces where people can interact with each other and with nature; and, small urban blue spaces (e.g., ponds or creeks) may be utilized for recreation or contribute to the perceived scenic beauty or “naturalness” of urban landscapes. Such cumulative experiences with green spaces at a local or neighborhood scale can thus greatly contribute to the overall mental health of urban residents.

In addition, we did not find any relationship between landscape diversity (the variety and abundance of green-space types) and psychological distress. However, we only examined three types of green space (tree, grass, water) in our assessment of landscape diversity, whereas some previous studies that found this sort of relationship had evaluated a wider array of green land covers (e.g., deciduous, evergreen, and mixed forest types). Our simple classification of green space may thus have failed to capture landscape diversity adequately, thereby undermining our effort here to explore the effects of green-space diversity on mental health.

Nevertheless, we did find some significant relationships between our green-space configuration metrics and psychological distress (table 14). For example, we found a negative association between the mean nearest-neighborhood distance of treed areas and psychological distress: larger distances between treed areas appeared to be associated with better mental health. This may seem counterintuitive, but in Chicago, as with many large metropolitan areas, a large distance between treed areas occurs because of the existence of a few, large urban parks or urban forests which tend to be located at a distance from residential or commercial areas. Despite their distance from these areas, urban forests can still be a haven for city dwellers who have been exposed to unhealthy or unsafe environments, since a forest enclosure provides many people with a sense of safety and comfort (Stigsdotter et al., 2017). Our study also found that the size of water bodies exhibited a positive relationship with psychological distress: smaller water bodies appear to be correlated with lower psychological distress compared to larger water bodies. Like urban green spaces, the presence of water in the landscape has been widely thought to have a restorative effect (Dempsey et al., 2018; Nutsford et al., 2016; Vert et al., 2020). Although we did not find a relationship overall between the percentage of water in the landscape and mental well-being, the spatial distribution of water bodies (here the size distribution of water bodies) can help to explain the positive association between smaller water bodies and mental health. In many U.S. metropolitan areas, small ponds and creeks in neighborhood parks may contribute greatly to the mental restoration of residents, given that people are more likely to visit nearby, accessible recreational water features more often than larger water bodies (e.g., wetlands, rivers, and lakes) (Chen and Yuan, 2020; Völker et al., 2018).

Our study also examined the relationship between the spatial configuration of total green space and psychological distress. We found that the aggregation of total green space (as assessed by the clumpiness index) was positively associated with psychological distress (table 14); in other words, several smaller green spaces (disaggregated green space) can effectively mitigate psychological distress compared to a single large green space. These findings add to a growing body of evidence in the ongoing SLOSS debate (several small versus a single large green space) in landscape planning. Our results are inconsistent, however, with previous studies showing that a single large green space provides more mental health benefits for residents (Akpinar et al., 2016; Nutsford et al., 2013). In the context of a metropolitan city like Chicago, the effect of formal urban green spaces (e.g., local and neighborhood parks) on mental health is limited since the provision of a large park (i.e., Humboldt Park) that has well-equipped and maintained recreational facilities is disproportionately distributed across neighborhoods. On the other hand, a large number of small urban green spaces can be more effective in improving mental health because residents would be more likely to encounter these in everyday life, including informal urban green spaces (e.g., vacant lots, roadside trees), private/community gardens, and pocket parks, regardless of neighborhood income level. Studies have shown that even small but cumulative exposures to nature can have positive mental health benefits for urban residents (Ekkel and de Vries, 2017; Engemann et al., 2019). Moreover, nearby green spaces can promote informal social interactions and contact with neighbors, thereby encouraging people to visit these spaces more regularly and increasing their sense of 'belonging' which is known to have positive mental health benefits (de Vries et al., 2013; Kingsley and Townsend, 2006). Another important aspect unique to North American neighborhoods is the dependence on automobiles for commuting and transportation (Filion, 2010; Terando et al., 2014). Accordingly, people are more likely to encounter informal urban green spaces while passing by in their cars. As a window view of nature can also promote mental restoration (Kaplan, 2001; Li and Sullivan, 2016; Lottrup et al., 2015), the exposure to urban green spaces through the dashboard window may similarly contribute to the mental restoration of urban residents.

Consistent with previous studies, we found that both social and environmental factors are also associated with the mental health of residents. For example, we found that population density was positively associated with psychological distress, consistent with previous studies that have suggested that living at high population densities could lead to greater mental health problems (Chen et al., 2015; Wang et al., 2020; Williams, 1994) and that crowded environments induce greater worry and stress (Hassan, 1977; Laird, 1973). The results of our study also showed that there was a strong association between SES and psychological distress. This is consistent with previous research that likewise found a robust relationship between SES and mental health (Akpinar et al., 2016; Fan et al., 2011; Larson et al., 2018; Ward Thompson et al., 2016). Individual social factors greatly affect one's health status since they determine access to important resources (e.g., medical centers) that may help to mitigate or prevent health risks (Link and Phelan, 1995). Our study also found that the individual perception of neighborhood safety was significantly correlated with psychological distress: individuals who felt safe in their neighborhood are less likely to experience psychological distress. One explanation for this relationship is that neighborhood safety can increase physical activity and social cohesion (Wang et al., 2019c), which in turn reduces mental health risks. In addition, the neighborhood social environment such as the sense of neighborhood belonging can influence the mental health of residents. Residents who feel part of their neighborhood tend to have fewer psychological problems. Neighborhood belonging can embody social support (e.g., seeking help) and have emotional release (e.g., talking about personal problems) for those who with mental health problems and such environments could promote better mental health (Kloos and Townley, 2011; Young et al., 2004).

Limitations and future directions

A major strength of our study lies in its attempt to illuminate the association between mental health and the composition and configuration of urban green spaces within a high-density metropolitan area, based on the application of landscape metrics to a high-resolution land-cover dataset. Based on our findings, several potential measures can be taken with respect to landscape planning to minimize the mental health risks of urban residents. For a large metropolitan city like Chicago, one recommendation that follows from the results of our study is to maximize the number of small urban green spaces that can be created. Small accessible green spaces, whether formal (e.g., gardens and pocket parks) or informal (e.g., street trees, green verges), can provide restorative benefits even through passive activities such as when people walk or drive by. Second, the establishment of large urban forests or protection of forested natural areas (e.g., Forest Preserves of Cook County) can play a significant role in minimizing mental health risks of urban residents, given that urban forests can promote a sense of peace and restoration (Furuyashiki et al., 2019); a mental and physical escape from an otherwise stressful urban environment. Third, our findings suggest that it would be beneficial to protect small water bodies (e.g., ponds, creeks) given their association with greater mental well-being, even in a major metropolitan area adjacent to one of the largest freshwater lakes in the world (i.e., Lake Michigan). Cities should engage in policy making for an effective green infrastructure program in order to help create the systematic connections across various urban green types and forms, including small-to-large, green-and-blue spaces.

Nevertheless, we acknowledge several limitations that may have hampered our efforts to develop a more robust spatial analysis of the relationship between the distribution of urban green spaces and mental health. First, the HCS does not contain specific geo-locations of respondents. This significantly limited our ability to verify the spatial characteristics of respondents' locations and their individual engagement with urban green spaces. It is not known how much cumulative exposure to green space people experience daily in their commute from home to work, for example. In future research, using geo-location data to track people's actual patterns of green-space usage will enhance the accuracy and reliability of these measurements. Second, the HCS is a pooled time-series of cross-sectional data from 61 community areas in Chicago. Although pooled data have the advantages of large sample sizes and statistical power (van der Steen et al., 2008), our dataset still has cross-sectional study characteristics that limit drawing causal links as well as the long-term effects between landscape patterns and psychological distress. In this respect, longitudinal and experimental studies are needed to better explore the relationships between humans and nature. Third, this study did not differentiate between natural (e.g., forest, wetland) and amenity (e.g., public park) green spaces. We acknowledge that amenity urban green spaces might be more accessible than natural urban green spaces. It is entirely possible that urban residents more frequently visit amenity green spaces for recreational purposes and socialization with their friends and neighbors. In previous studies, the frequency and duration of visits to urban green spaces promoted the mental health of urban residents (Ayala-Azcárraga et al., 2019; Giles-Corti et al., 2005; Waltham et al., 2014). Thus, future studies should take into account the typology of urban green spaces.

4.5 Conclusion

It is a widely held view that urban green space can contribute to the mental health of urban residents, but the link between the landscape composition and configuration of urban green spaces and mental health are far less studied. Our study explored how the configuration and composition of urban green spaces were associated with a measure of psychological distress in urban residents inhabiting a densely populated region within the city of Chicago. A total of 6,405 respondents from 61 community areas were analyzed for this study. Our findings indicated that respondents reported fewer psychological problems within urban landscapes where green space exhibited a greater distance between treed areas and possessed smaller bodies of water. In terms of total green space, disaggregated urban green spaces had more of a positive impact on the mental health of urban residents than when green space was aggregated (i.e., a single large green space). The landscape pattern of urban green spaces can thus influence mental health. It is therefore crucial for urban and landscape planners to wisely consider the distribution of urban green spaces—and not just the total amount of green space—as one means of reducing mental health risks.

Conflict of Interest Statement

The authors have no financial disclosures to declare and no conflicts of interest to report.

Acknowledgment

We thank the Chicago Department of Public Health for providing the Healthy Chicago Survey data used in this study. The Department specifically disclaims responsibility for any analyses, interpretations, or conclusions. We thank Professor Jin Lee for giving us advice on statistical analysis.

Chapter 5 - Conclusion

5.1 Summary of key findings

Two independent studies in this dissertation addressed how spatial characteristics of urban green space are associated with the mental well-being of residents. In the first, an experimental study was used to illuminate how a biodiverse campus green space can affect the mental well-being of students through visual and auditory stimuli. The experimental study proposed three main research hypotheses: 1) Groups of students exposed to a high-biodiversity environment report greater restorative and positive moods than those exposed to a low-biodiversity environment; 2) an integration of sound and visual stimuli moderates the effects of restorative and positive mood states on students; and 3) a combination of visual and auditory stimuli appears to have an interaction effect on restorative and mood states in students.

The results of this study revealed that the single factor of stimuli (either visual or sound) has an impact on negative mood states. However, there was a significant interaction effect between visual and auditory stimuli. This interaction effect might explain that a higher mental restoration effect was found in high-biodiversity environments with the presence of sound. This study reveals that the level of biodiversity plays a critical role in the mental restoration of college students.

The second study presented in this dissertation investigated how landscape patterns are associated with mental health problems in a metropolitan city. The observational study proposed four main research hypotheses: 1) In urban landscapes, trees will be associated with mental health in the strongest way among all types of green cover; 2) the presence of a greater variety of green-space types within the urban landscape is associated with better mental health; 3) urban landscapes with large, connected, and/or aggregated green spaces (either trees, grass, or water) are associated with better mental health; and, 4) there is a significant relationship between better mental health and urban landscapes that have a significant amount of total green space (trees, grass, and water combined), or those that have connectivity and/or aggregated distribution of green spaces.

It turns out that there is no relationship between mental health and proportions of urban green space types. In addition, this study did not find any link between landscape diversity (the variety and abundance of green spaces) and mental health. However, a significant relationship was found between green space configuration metrics and mental health. The results of zero-inflated Poisson and generalized linear mixed models indicated that a greater distance between tree canopy, smaller water bodies, and disaggregated total green space was related to better mental health factors among Chicago residents. These findings illuminate the importance of evaluating the spatial distribution of urban green space, rather than simply considering the amount of urban green space for landscape planning in metropolitan cities.

Table 15 summarizes the findings based on the study hypotheses.

Table 15 Summary of key findings

Study	Hypothesis	Results
Study 1 (Experimental study)	Hypothesis 1: student groups exposed to a high-biodiversity environment have higher restorative and positive mood states than those exposed to a low-biodiversity environment.	Not significant
	Hypothesis 2: a combination of sound and visual stimuli moderates the effects of restorative and positive mood states on students.	Not significant
	Hypothesis 3: a combination of visual and auditory stimuli appears to have an interaction effect on restorative and mood states in students.	There is a significant interaction effect in visual and auditory stimuli
Study 2 (Observational study)	Hypothesis 1: among all types of green cover in the urban landscape, trees will have the strongest correlation with mental health.	Not significant
	Hypothesis 2: the presence of a greater variety of green space types within the urban landscape is associated with better mental health.	Not significant
	Hypothesis 3: urban landscapes with large, connected, and/or aggregated green spaces (either trees, grass, or water) are associated with better mental health.	Association with mental health problems; Tree distance (-) Water size (+)
	Hypothesis 4: there is a significant relationship between better mental health and urban landscapes that have a significant amount of total green space (trees, grass, and water combined), or those that have connectivity and/or aggregated distribution of green spaces.	Association with mental health problems; Total green space aggregation (+)

5.2 Contributions of the study

This dissertation yields contributions and implications that fill the knowledge gap of existing literature on human well-being landscape design and planning. Using both experimental and observational studies, this dissertation offers a better understanding of the mental restoration mechanisms experienced by humans in the environment from the local site to urban landscape scales. By conducting studies in both controlled and natural settings, this dissertation can provide practice- and evidence-based implications for both landscape architects and urban planners to enhance mental well-being. A further goal of this study was to identify how landscape patterns and biodiversity influence human well-being as a means of finding a balance between human use and conservation of nature.

5.2.1 Study 1

The primary contribution of the biodiversity study (Study 1) is to illustrate how campus green space can affect students' mental well-being by illuminating the causal relationship between human perception and nature. The pre- and post-intervention effects tested whether the environmental exposure was effective in changing the mental status among college students using a simulated 360-degree view video. The results showed there was a statistically significant difference in mental status before and after the intervention. This reveals that simply watching nature videos enables a reduction in negative mood states, encouraging mental restoration.

Furthermore, this study employed a web-based survey platform to conduct experimental research. Due to the COVID-19 pandemic, laboratory-based or in-person experiments were limited. A web-based survey offered new possibilities and applications in experimental research within the area of nature and well-being studies. With the rise of advanced immersive visualization technologies (e.g., AR/VR), the accuracy, validity, and reliability of online platform surveys can be improved. Thus, this study can bridge the gap between a lab-based experimental study and a web-based experimental study.

This study also explored whether the level of biodiversity can promote mental well-being through multisensory stimulation. Unlike previous literature that mainly considered visual stimuli in an experimental setting, this study investigated visual and auditory stimuli in different levels of biodiversity. Although this study showed no statistically significant effects in either the main effect of natural sound or biodiversity (visual stimuli), the findings indicated that a mental restoration effect among college students was found in the high-biodiversity environment with the presence of sound. The interaction effect between visual and auditory stimuli might explain the results of this study. This fact illustrates the importance of the multisensory approach in biodiversity and mental well-being research.

According to this study, landscape design may contribute to the mental well-being of urban dwellers in a number of ways. Many modern American universities have a similar type of campus green space inspired by the European Beaux-Arts tradition, including manicured lawn areas, courtyards, and quadrangles. Going beyond finding the role of urban green space in affecting mental well-being, this dissertation illuminates the role of campus green space biodiversity. To maximize the benefits of campus green space on the mental well-being of students, landscape architects and university administrators need to consider biodiverse campus green space. The evidence presented in this study supports the idea that a biodiverse green space (e.g., high species richness) can be more effective for the mental restoration of college students than a low-biodiversity environment. This restoration effect can be determined not only by visual stimuli but also by auditory stimuli. The integration of visual and auditory stimuli in high-biodiversity environments contributes to a greater degree of mental restoration.

Based on this finding, landscape architects should consider using a wide array of plant species that may restore local wildlife habitats for animal species (e.g., birds, and insect pollinators). A biodiverse campus green space can bring more animal species, increasing landscape fascination as well as a sense of calm through natural sound (e.g., bird songs). Considering that many universities have limited areas to expand their campus green space, the transformation from manicured lawn areas to native meadow gardens can be a wise approach toward increasing biodiverse campus green space.

5.2.2 Study 2

The landscape pattern study (Study 2) contributes to the understanding of the role of the spatial distribution of urban green space on mental health. The findings of this study in particular move forward long debates about the relationship between the quantity of urban green space (e.g., amount, accessibility) and mental well-being. In many previous studies, urban green spaces are generally recognized as homogeneous land covers, which are typically divided into either natural or built environments. In urban neighborhoods, however, there are a variety of configurations (e.g., size, aggregation, distance) and compositions of urban green spaces (e.g., trees, grass, water). The study demonstrated that the spatial distribution of urban green space has a significant effect on mental well-being by increasing exposure to nature and promoting restorative effects.

This study employed landscape pattern analysis methods derived from landscape ecology. Landscape metrics have been used in a wide array of fields, including ecological and geographical studies (Wu, 2004). This study especially contributes to the application of landscape metrics in analyzing the spatial distribution of urban green space that might be associate with the mental well-being of urban residents. To my knowledge, little research has attempted to apply landscape metrics to mental health studies.

The landscape design and planning implications of this study can potentially improve the mental well-being of urban residents. Many metropolitan cities have difficulty providing urban green space, raising the issue of environmental justice. Although many previous studies highlight the importance of urban green space for mental well-being, metropolitan cities have a limited budget to provide residents with nearby nature in their neighborhoods. The evidence presented in the landscape-pattern study addresses how the spatial distribution of urban green space is associated with mental health problems, going beyond the debate on simply the provisioning of accessible nature or green space to urban residents. The findings presented in this study suggest aspects of landscape planning that can maximize the benefits of existing nature in urban areas.

The findings of this study indicate that landscape planners and policymakers need to consider disaggregated green space (in other words, numerous smaller green spaces) for enhancing the mental well-being of urban residents, especially in the context of metropolitan cities. Both informal (e.g., green verges, vacant lot green space) and formal (e.g., garden and backyard) green spaces can give people brief but cumulative restorative benefits while they are passing by. Policymakers and landscape planners can initiate the idea of transforming a vacant lot and leftover space to create small-scale urban greenery.

Better mental health can be achieved through the neighborhood environment by implementing greater distances between tree canopies. An urban forest/woodland creates a forest enclosure that creates a sense of safety and comfort. Thus, the protection or provision of an urban forest/woodland can promote the mental health of urban residents. Policymakers and natural resource managers can balance the demand for public use of forest preserves with the protection of natural resources.

Providing small-scale bodies of water in urban areas can improve the mental health of urban residents. Nearby blue spaces like recreational water features (e.g., lakes, ponds, creeks) in urban parks give people more opportunities to experience restorative effects than larger water bodies (e.g., wetlands, canals). In the context of metropolitan areas, accessible blue space allows people to more frequently use outdoor recreational water, which results in increased physical activity and exposure to nature. The study's findings encourage urban and landscape planners to provide small-scale bodies of water in neighborhood urban parks.

5.3 Limitations and future research

This dissertation's findings raise several questions that should be addressed in future research. The results of the biodiversity study (Study 1) revealed a mismatch between perceived biodiversity and actual biodiversity. In other words, participants were not able to properly compare high-biodiversity environments with low-biodiversity environments; they had a higher perception of biodiversity in an environment with low biodiversity, and vice versa. Therefore, future studies need to provide participants with more immersive environments. Because of the COVID-19 pandemic, this study was not able to implement the on-site experiment in the field. An online survey significantly limits the amount of environmental exposure and the ability to control experimental conditions. In future research, an on-site experiment or lab experiment using immersive visualization technology (e.g., AR/VR) is strongly encouraged, as it would provide a more immersive environment for participants.

Although this study measured psychological responses using validated survey instruments, future studies need to measure physiological responses (e.g., skin conductance level responses, brain waves, and heartbeat rates). Such objective indicators can support the body's automatic reactions to environmental exposure. Both subjective and objective measurements can help assess the comprehensive restorative mechanism based on physiological and psychological responses.

Future studies can also investigate the mediation effects in actual biodiversity, perceived biodiversity, and psychological responses. Due to the limitation of the dataset, this study could not perform a mediation-effect analysis. Actual biodiversity in this dissertation is a binary variable (low vs. high), while perceived biodiversity involves continuous variables. The mediation analysis can help to gain a better understanding of whether perceived biodiversity matters for mental well-being, independent of actual biodiversity.

There are several limitations in the landscape pattern study (Study 2) as well. The health dataset provided by the Chicago Department of Public Health did not include the geolocation of each respondent's home address. This study is limited in identifying the individual residence-based buffer within walking distance of a neighborhood. A future study could explore the actual route of each respondent by using GPS tracking devices. The information on cumulative green space exposure from survey participants can be obtained through a geolocation-based dataset.

This study utilized a pooled time series of cross-sectional data. Pooled time data can offer a large sample size and statistical power, while the characteristics of cross-sectional data do not explore causal relationships and long-term effects in this study's statistical model. In future studies, lab experiments and longitudinal studies are highly encouraged to overcome the limitations of this study.

Although this study investigated the association between types of urban green space and psychological distress, it did not distinguish between natural (e.g., woodland, wetland) and amenity (e.g., parks, recreational areas) green space. Future studies need to differentiate the unique characteristics of urban green space that are associated with psychological responses. For example, amenity green spaces could be used by urban residents as they may be more accessible in their neighborhood environments.

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