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Walking Through Green and Grey: Exploring Sequential Exposure and Multisensory Environmental Effects on Psychological Restoration

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Abstract

Urban environments are increasingly recognized for their potential to support psychological restoration, yet most studies assess green and grey spaces in isolation and rely on static, lab-based measures. This study introduces a multi-layered analytical framework that integrates experimental walking, momentary perception tracking, and machine learning to investigate how multisensory urban features shape restoration. Conducted on a university campus, the experiment exposed 20 participants to sequential grey-green-grey walking routes. Restoration was measured through pre/post psychometric surveys, heart rate variability (HRV), and minute-level micro-surveys during walking. Results reveal three key insights: (1) green exposure induces a short-term “inoculation effect”, with restorative benefits persisting even after re-entering grey environments; (2) visual features emerged as the most influential predictors of restoration, followed by noise and microclimate; and (3) solar irradiance — when balanced with moderate temperature and humidity — positively contributing to relaxation and stress reduction. Beyond experiments, we simulated design interventions on low-restoration scenarios using a large language model to enhance visual attributes, followed by predictive evaluation via machine learning. These simulations showed measurable improvements in predicted restoration, validating a data-driven approach for environmental optimisation. This research contributes to neurourbanism by bridging spatial sensing, physiological feedback, and AI-driven interpretation. It offers practical guidance for creating psychologically supportive urban environments — such as prioritising early green exposure and mitigating noise pollution — and introduces a replicable pipeline for evaluating restorative potential in future urban design.

Keywords: built environment, environmental psychology, multisensory perceptions, neurourbanism, mental well-being, microclimate

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1. Introduction

Urbanisation has profoundly altered the conditions of daily life, contributing to a rise in psychological distress, including anxiety, mood disorders, and chronic stress-related conditions (Luo and Jiang, 2022; Lei et al., 2025). Urbanites have to contend with dense environments, traffic congestion, noise, and limited access to natural spaces—stressors that increasingly challenge mental well-being (Dong and Qin, 2017; Wang et al., 2021; Le et al., 2024; Korpilo et al., 2024). In response, the concept of psychological restoration — defined as the process of recovering depleted emotional, cognitive, or physiological resources through interaction with supportive environments — has emerged as a critical aspect in urban planning and design (Hartig et al., 1997; Kaplan, 1995; San Juan et al., 2017).

Natural environments have been long recognised as the key driver of psychological restoration, examined in theories such as Attention Restoration Theory (ART) and Stress Recovery Theory (SRT) (Kaplan and Kaplan, 1989; Ulrich, 1984). A large body of literature has documented the restorative benefits of nature exposure, including improved mood, reduced stress, and cognitive recovery (Kaplan, 1995; Berman et al., 2014; Li et al., 2023; Pazhouhanfar and M.S., 2014; Brown et al., 2013a). However, many of these studies treats green and built environments in isolation, often positioning grey and built settings as control conditions for assessing nature's momentary restorative effects (Berman et al., 2008; Kajosaari and Pasanen, 2021). In real life, individuals encounter and perceive a continuous mix of green and grey environments as they move through urban space. Recent walking experiments have expanded to include mixed urban environments, encompassing natural, semi-natural, and grey built-up areas, or mixed-use environments, while findings still focuses on comparing different route sections characterized by land use, green/blue coverage, or spatial configurations (Zheng, 2018; Chrisinger and King, 2018; Zhang et al., 2025). While people's movement and walking are dynamic, the experiences they acquire in specific settings may have lasting benefits, functioning as a continuous process rather than isolated moments of restoration. Such phenomenon raises a critical yet under-explored question: Do the psychological benefits of green exposure influence how people react to subsequent built settings?

Several laboratory studies suggest that prior exposure to nature may enhance psychological resilience to subsequent stress which is sometimes referred as a "green inoculation effect" (Parsons et al., 1998; Brown et al., 2013b; Wilkie and Clouston, 2019). Nevertheless, these findings are based on artificial settings using abstract stress tasks, not real-world transitions between green and built environments.In particular, the green inoculation effect, where exposure to green environments has lasting benefits for subsequent walking in less restorative environments (e.g., grey built-up areas), remains rarely examined in real-world contexts, representing a key gap in the state-of-the-art discourse. Filling this gap can help inform urban design strategies that promote psychological resilience and support mental well-being and quality of life in everyday environments (Lei et al., 2025; Sheikh and van

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Ameijde, 2022).

Restoration is not exclusive to natural settings; well-designed built environments can also support psychological well-being (Weber and Trojan, 2018). Urban environments are inherently complex, encompassing a diversity of physical objects and spatial forms (Chen et al., 2021). While monotonous, dense, or poorly designed urban spaces may negatively impact psychological well-being (Stigsdotter et al., 2017; Subiza-Pérez et al., 2021), recent studies have identified specific visual characteristics within built environments that support restoration. For instance, openness, street lighting, and coherent architectural features can enhance restorative experience and psychological recovery in urban environment (Zhang et al., 2024b; Ma et al., 2024; Wu et al., 2024). However, real-world environments are rarely experienced through vision alone (Herzog and Kaplan, 1998; Ito et al., 2024). Increasing evidence indicates that other sensory dimensions, particularly urban soundscapes (Ojala et al., 2019; Jeon et al., 2023) and thermal comfort (Rathmann et al., 2020), significantly shape restorative perceptions. Meanwhile, most research tends to rely on controlled laboratory conditions or static simulations, implying limitations in reflecting the reality. Real-world walking experiments often utilize route or scenario-level comparisons, but these studies lack finer resolution and fail to address the combined impact of multisensory factors during walking (Asim et al., 2023; Zheng, 2018; Stigsdotter et al., 2017). Therefore, the understanding of how individuals experience and respond to multisensory stimuli during everyday urban activities (e.g. walking) remains limited.

The proliferation of artificial intelligence and neurourbanism advances the studies on psychological restoration. Machine learning (ML) and explainable artificial intelligence (XAI) have been widely employed to investigate the complex and non-linear relationships between built-environment characteristics and human comfort, affect, safety, and well-being (Lei et al., 2025; Ji et al., 2023; Zhou et al., 2023). These computational tools offer new opportunities for examining how multisensory environmental features interact to influence restoration (Ma et al., 2024). In parallel, advancements in wearable sensors enable ecological momentary assessment, providing continuous, real-time physiological and perceptual data on how individuals respond to urban spaces (Tartarini et al., 2023; Shiffman et al., 2008; Liu et al., 2023). Such methods have provided ecologically valid insights into how physiological stress markers (e.g. HRV) vary dynamically across different urban contexts (Asim et al., 2023; Chen et al., 2024). Combining computational tools with wearable sensors thus facilitates a deeper and more integrated understanding of human-environment interactions, complementing traditional self-report approaches. Despite these advancements, several challenges persist:

- Lack of empirical evidence on whether green exposure confers ongoing restorative benefits — psychological and physiological — during subsequent grey-space exposure;

- Limited quantitative understanding of how multisensory environmental features jointly contribute to perceived restoration;

- Lack of more context-aware, finer-grained, momentary assessments of restoration in real-world, walking-based studies.

To address these gaps, this study has developed a multi-scale analytical framework integrating real-time sensing, environmental feature extraction, physiological tracking, and explainable machine learning. The framework aims to capture a holistic reflection of urban characteristics and explore the interaction between restoration and people's surrounding in a spatially explicit manner. By combining quasi-experiment with perception momentary assessment, we conducted a walking study in a varied environment area, capturing restoration responses across and within green and grey route sequences. Evaluating the feasibility of our framework, we implemented it on a university campus, which is regarded as a microcosm of urban contexts with environmental and contextual richness. The study aimed to: (1) examine how sequential exposure to different urban settings influences restorative outcomes at route level; and (2) evaluate how multi-sensory environmental features, including visual, acoustic, and microclimatic variables, shape momentary restoration at the location level. Further, we explored how environmental design interventions can enhance restorative potential through scenario optimisation, aligning with a broader discussion of planning and policy implications.

The contributions of this research are multifaceted. First, we investigate, for the first time, green-grey exposure sequences in real-world walking contexts. This research reveals how restorative effects may accumulate, persist, or diminish as individuals move through mixed urban settings. Analysing sequential exposure introduces a new paradigm in restoration research, shifting from static comparisons to the impacts of dynamic exposure. Second, our work introduces a multidimensional framework that integrates environmental and contextual features to assess their combined effects on momentary restoration. In this regard, we provide finer-grained insights of how specific urban features contribute to individual's psychological benefits. Third, incorporating scenario optimisation via large language model and explainable machine learning, this work establishes an interpretation of how human restoration is affected by diverse urban settings. Leveraging such technique enables not just prediction, but also offers an addition to understanding the significance of urban features in restoration. Fourth, the findings from this work can inform evidence-based strategies in urban planning and design, guiding interventions that promote mental health through spatial sequencing and multisensory enhancement. These contributions offer practical insights for creating more restorative and mentally supportive urban environments.

2. Literature review

2.1. Environmental factors in psychological well-being

Visual environment and streetscape features. Urban visual environments strongly shape emotional states, perceived safety, and spatial behaviour. Features such as greenery, openness, and architectural coherence influence mood, comfort, and attention (Ewing and Handy, 2009; Kaplan, 1995). With advances in computer vision, street view imagery (SVI) enable fine-grained assessments of pedestrian-level elements—vegetation, sky openness, and water, using semantic segmentation techniques (Biljecki and Ito, 2021; Ma et al., 2021; Zhang et al., 2024a). In addition, scene depth, which reflects the spatial layering and openness of an environment, has been associated with affective responses such as calmness and navigational ease. Computational metrics for depth can offer insights into how people interpret environmental legibility and complexity (Asim et al., 2023). Low-level image features (e.g. hue, brightness, and visual clarity) also influence spatial judgments and emotional reactions, providing scalable indicators of urban aesthetic quality (Celikors and Wells, 2022; Rossetti et al., 2019; Ito et al., 2024). Computational approaches pave the way for scalable, objective evaluation of visual assessment, offering significant potential for linking visual characteristic of environments with psychological outcomes.

Urban soundscape and environmental noise. While environmental perception research has traditionally emphasised visual stimuli, the auditory dimension, plays an equally vital role in shaping human experience and well-being (Korpilo et al., 2024). Urban soundscapes encompass the acoustic character of outdoor environments, including both natural and anthropogenic sounds, and have been shown to significantly influence mood, mental well-being, and quality of life (Kang, 2006). A growing body of evidence suggests that noise exposure — especially from traffic and mechanical sources — can elevate stress levels and contribute to long-term mental health risks (Zhao et al., 2023; Xu et al., 2024b; Jeon et al., 2021). In this study, momentary noise levels are directly measured in situ and analysed as a key explanatory variable affecting perceived restoration during walking.

Thermal comfort and microclimate in urban settings. Urban microclimates impact outdoor comfort, walkability, and psychological states, especially as global warming and urban heat island effects intensify (Xi et al., 2012; Liu et al., 2023). Research increasingly explores how thermal stress affects health, spatial behaviour, and perceived well-being (Chen et al., 2023; Xu et al., 2024a). Key parameters — air temperature, humidity, wind speed, and solar irradiance — are typically measured in climate-sensitive urban monitoring and design (Bröde et al., 2012; Fujiwara et al., 2024a). These are strongly influenced by local morphology, including vegetation, built form, and surface materials (Berry et al., 2013; Middel et al., 2014; Yuan et al., 2021). Solar irradiance is especially impactful, directly affecting pedestrian experience and thermal stress in exposed spaces (Lee and Mayer, 2021; Azegami et al., 2023). Recent methods now incorporate vegetation shading into irradiance modelling for finer-grained assessments (Fujiwara et al., 2024b).

2.2. Restorative processes in everyday urban environments

2.2.1. Restoration and measures

Urban restorative environments can help individuals recover from the psychological and physiological burdens of everyday stressors, including cognitive fatigue, emotional strain, and environmental discomfort (Dong and Qin, 2017; Weber and Trojan, 2018). Restoration refers to the beneficial changes in psychological or physiological states following exposure to supportive environments (Hartig and Staats, 2006). These changes are typically assessed across perceptual, affective, and physiological dimensions (Cheng et al., 2025).

Perceptual restoration, often treated as the core outcome, is commonly assessed through perceived stress recovery and mental clarity. The Restoration Outcomes Scale (ROS) is a widely used instrument that captures self-reported changes in stress reduction, relaxation, and attentional recovery following environmental exposure (Subiza-Pérez et al., 2021; Kajosaari and Pasanen, 2021).

Affective restoration focuses on changes in mood and emotional state. The Stress Recovery Theory (SRT) suggests that natural and low-threat environments reduce arousal and support positive affective shifts. Tools such as the Positive and Negative Affect Schedule (PANAS), the Profile of Mood States (POMS), and the Mood Adjective Checklist (MACL) are commonly employed to measure these shifts across various restorative settings (Jeon et al., 2021; San Juan et al., 2017; Bornioli and Subiza-Pérez, 2023).

Physiological restoration involves tracking bodily responses that reflect the autonomic nervous system (ANS) balance during recovery from stress. Heart rate variability (HRV), a key marker of autonomic regulation, is widely used in restoration studies to measure the body's physiological recovery. Higher HRV typically indicating greater relaxation and improved physiological recovery (Weber and Trojan, 2018; Xiang et al., 2021). HRV has been validated in numerous studies as a reliable indicator of psychophysiological restoration and positive affect, making it a cornerstone in studies of mental and emotional well-being (Jeon et al., 2023; Asim et al., 2023; Kexin Sun et al., 2024; Liu et al., 2022; Stigsdotter et al., 2017; Roe et al., 2019). Other metrics commonly used to assess physiological restoration include skin conductance and electrodermal activity (EDA), which measure sympathetic activation in response to stress (Zhang et al., 2025). Additionally, blood pressure and salivary cortisol levels are often measured to assess the biological response to stress and the body's ability to return to a balanced state after exposure to stressors (Asim et al., 2023; Jeon et al., 2023; Chen et al., 2024).

While perceptual assessments have dominated the literature, affective and physiological outcomes remain less explored, considering their critical roles in capturing the multisensory and embodied experience of urban environments. An integrated evaluation that combines these three dimensions is essential for a comprehensive understanding of how urban spaces contribute to restoration and mental well-being.

2.2.2. *Restorative benefit of green pre-exposure*

Exposure to green spaces has been consistently shown to enhance psychological restoration—improving mood, attention, and physiological regulation (Kaplan, 1995; Berman et al., 2014; Li et al., 2023). These effects are often observed even after short interactions with nature (Pazhouhanfar and M.S., 2014; Brown et al., 2013a). Reviewing real-world walking studies, much of the existing research focuses on the restorative benefits of natural exposure or green exercise. Previous studies utilizing pre-post quasi-experiments have established that walking in natural environments increases perceived restoration, HRV, while reducing electrodermal activity, blood pressure and heart rate (Berman et al., 2008; Ning et al., 2023; Zhang et al., 2025; Liu et al., 2021). However, most walking experiments treat urban (grey-dominant) environments as control groups (Berman et al., 2008; Stigsdotter et al., 2017; Olafsdottir et al., 2017), focusing primarily on the direct comparison between natural and urban environments.

A growing body of laboratory studies suggests that nature's restorative benefits can extend beyond immediate exposure, a phenomenon often referred to as the "green inoculation effect." This effect describes the capacity of prior green exposure to buffer against subsequent stressors. For instance, Parsons et al. (1998) found that participants who viewed natural drives recovered more physiologically and emotionally from a stress inducing math task compared to those who viewed urban scenes. Similarly, Brown et al. (2013b) reported that pre-exposure to natural imagery led to higher heart rate variability (HRV) during recovery from a cold pressor test, indicating enhanced physiological resilience. Complementary evidence from immersive photo and virtual reality studies further supports these findings. Wilkie and Clouston (2019) showed that participants who viewed nature before a cognitive challenge experienced smaller increases in negative mood than those exposed to urban imagery. Collectively, these results highlight that even brief green exposure can foster short-term psychophysiological resilience, softening the impact of later stressors or overstimulating environments.

Yet, these findings remain largely confined to controlled environments, relying on passive visual stimuli and artificial stressors. More recently, walking experiments have expanded to more complex urban environments, where artificial or built-dominant spaces such as plazas (Subiza-Pérez et al., 2021; Payne and Bruce, 2019), living areas (Zhang et al., 2025; Chrisinger and King, 2018), and study spaces are compared with green and blue spaces within campuses (Asim et al., 2023). While these studies generally show that artificial or built environments provide less restorative value compared to natural or green spaces, it is important to note that this effect is not universally negative and can vary based on the design characteristics of the space (Asim et al., 2023; Stigsdotter et al., 2017; Zhang et al., 2025).Despite this progress, gaps still remain in understanding the interaction between green and built environments in real-world settings. To the best of our knowledge, no existing walking experiment has explored the green inoculation effect in real-world urban environments, where prior exposure to green spaces may enhance resilience to subsequent built environments. This study addresses this gap by investigating the temporal dynamics of perceived restoration across sequential green and grey exposures in a walking experiment.

2.2.3. Urban environment and restorative effects

The restorative potential of urban environments is shaped by a range of sensory exposures—primarily visual, auditory, and climatic. While natural features such as vegetation, sky, and water are consistently associated with enhanced restoration (Herzog and Kaplan, 1998; Kaplan, 1995; Kajosaari and Pasanen, 2021; Gong et al., 2018; Helbich et al., 2019), the influence of built features has also gained increasing recognition (Cheng et al., 2025; San Juan et al., 2017). Urban environments are not inherently detrimental to well-being; rather, their restorative value depends on specific design attributes. For example, streetscapes with open views, moderate enclosure, and navigational clarity may promote psychological comfort and attention recovery. Features such as sky visibility and road openness have been associated with more favourable affective responses, whereas environments dominated by traffic, visual clutter, or hard paving may detract from restoration (Ma et al., 2024; Wu et al., 2024). These findings indicate that both natural and urban visual cues contribute to the restorative quality of everyday environments, depending on their composition and coherence.

Recent research has further incorporated depth and low-level visual features, such as hue, brightness, and texture complexity, which are processed early in the visual system and influence restoration indirectly through perceptual comfort (Celikors and Wells, 2022; Ma et al., 2023). For example, scene depth has been found to be positively associated with relaxation and restorative potential, possibly due to the lack of visual clutter or enclosure (Zhang et al., 2024c). Lighting conditions also play a role: balanced daylight enhances visual comfort, while excessive brightness may disrupt perceived restorative potential (Celikors and Wells, 2022; Ma et al., 2024).

Beyond vision, the acoustic environment contributes substantially to restorative experiences. Natural sounds—such as bird songs, water flow, and rustling leaves—have been shown to enhance affective and cognitive restoration, especially when paired with visually green spaces (Guo et al., 2022; Masullo et al., 2021). Conversely, traffic noise and urban mechanical sounds negatively impact perceived tranquillity, particularly among noise-sensitive individuals (Jeon et al., 2023; Ojala et al., 2019; Payne and Bruce, 2019).

Despite growing interest in urban sensory exposures, the influence of thermal environments on restorative outcomes has received comparatively less attention. (Bai and Jin, 2023) suggest that general thermal comfort can positively contribute to perceived restoration, while high thermal stress can diminish comfort and emotional responses (Bai and Jin, 2023). A recent study utilized physiological measures and semi-structured interviews to investigate the restorative benefits of campus landscapes during walking (Zhang et al., 2025). Through qualitative analysis, participants reported that thermal conditions, including temperature, wind, and solar exposure, affected their comfort. While quantitative, statistical analyses primarily focused on visual characteristics and restoration at the scene level, no objective thermal data were included. The objective, finer-grained thermal conditions' restorative value is still underexplored in real-world walking settings. However, to the best of our knowledge, no studies have systematically examined the role of finer-grained microclimatic variables on momentary restoration during real-world urban experiences.

Recent studies on walking experiments in urban environments have reported mixed effects on restorative benefits. On the one hand, grey-dominant environments (e.g., urban areas with high built elements) were found to provide less restorative benefits or even negative effects (Ning et al., 2023; Liu et al., 2021). On the other hand, walking experiments indicate that specific urban scenarios, such as urban squares (Subiza-Pérez et al., 2021), historical districts (Stigsdotter et al., 2017), and well-maintained waterfronts with tactical design interventions (Roe et al., 2019), have the potential to increase arousal, evoke positive affect, and contribute to cognitive restoration (Asim et al., 2023; Zhang et al., 2025). Most of these walking experiments focus on route-level or scenario-level insights, typically using pre-post quasi-experimental designs. However, a few studies have examined sections of routes (Zhang et al., 2025; Chrisinger and King, 2018), providing a finer-grained analysis of visual characteristics, land use, and spatial configurations. Despite these advances, there is still a significant gap in quantitative, high-resolution multisensory investigations (including visual, acoustic, and thermal) that assess momentary restoration in real-world urban experiences.

Reviewing the variety of restoration studies in urban environments, two important gaps remain. First, although green walking has been well-established as beneficial for evoking restoration during walking, it is still unclear whether prior exposure to green environments has a lasting, sequential effect (the so-called inoculation effect) when individuals further enter built-dominant environments, and how this effect benefits individuals psychologically and physiologically. Second, while the restorative benefits of urban environments are influenced by multisensory factors, most existing studies have focused on visual environments or static scenarios at specific walking stops. Less attention has been given to the dynamic, finer-grained impact of urban environments during walking, particularly in terms of a comprehensive quantitative multisensory momentary assessment of urban characteristics' restorative benefits.

This study addresses these gaps by providing quantitative evidence and a machine-learning-based analytical framework on how exposure sequences and multisensory environmental characteristics shape individual restoration over time during a walking experiment.

3. Data and Methods

3.1. Framework design

A campus-based walking experiment was conducted across three routes with varying environmental characteristics. Restoration was assessed through a combination of pre/post-walk surveys and high-frequency micro-surveys (see Section 3.4), capturing physiological, perceptual, and affective responses. Concurrently, environmental features (e.g. visual, acoustic, and microclimatic) were recorded using computer vision and sensor-based methods.

Three walking routes were designed to reflect different environmental typologies: Route 1 and Route 3 were visually grey-dominant, while Route 2 was green-dominant. These routes formed the basis for testing both sequential exposure effects and momentary restorative responses. At the route level, repeated-measures analyses and linear mixed models (LMMs) were applied to evaluate inter-route differences and covariate effects. At the location level, explainable artificial intelligence (XAI) techniques were used to interpret how multisensory environmental inputs shaped momentary restoration perceptions. Predictive models were then used to simulate design interventions and evaluate their effects. Figure 1 summarises the analytical workflow.

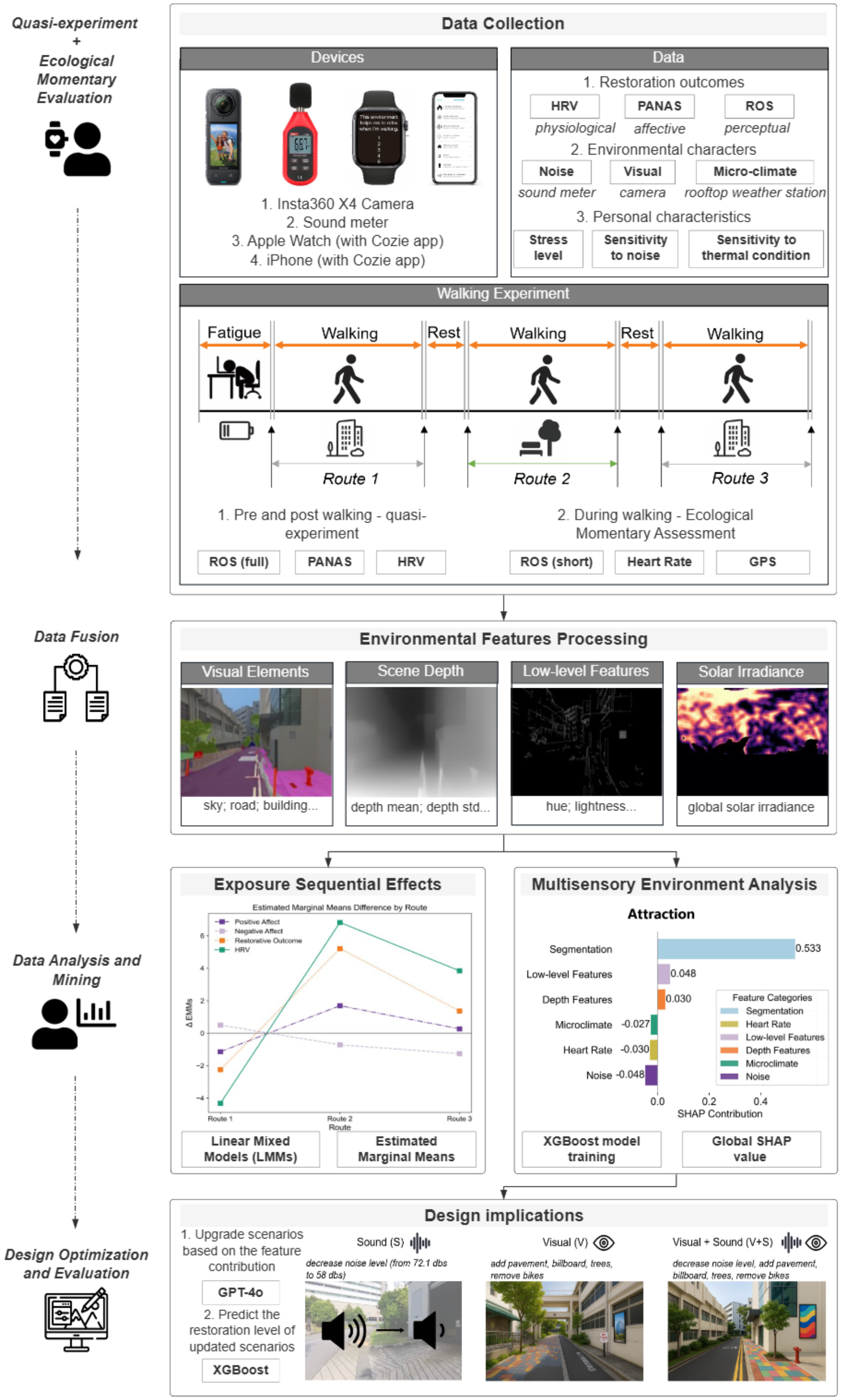

Figure 1: Analytical framework used in this study, combining walking-based restoration assessment, multi-sensory environmental feature extraction, and multi-level analysis using statistical models, explainable machine learning, and scenario simulation.

3.2. *Location*

3.2.1. *Case study: campus environment*

University campuses represent formative environments that many young adults engage with extensively after leaving their familial homes. These settings, which encompass both built and natural elements, are embedded within students' daily routines and may significantly influence their mental and physiological well-being (Cambaco et al., 2024). While previous research has highlighted the potential health benefits of nature exposure and urban form (e.g., (Jiang et al., 2022; San Juan et al., 2017)), the specific role of campus environments on university populations remains under-explored. The need to understand campus-based environmental influences becomes particularly salient in the post-pandemic context, where university students face elevated psychological and physiological health risks (Ding et al., 2024). In this study, we examined a university campus as a representative urban setting to explore how everyday exposure to urban environments may influence their restoration.

3.2.2. *Walking experiment route selection*

Three walking routes were selected in the campus of the National University of Singapore (NUS), around the College of Design and Engineering (CDE), as illustrated in Figure 2. Each route ranged from 431 to 452 metres in length and took about 10 minutes to complete at a moderate walking pace (Figure 2). During walking, participants paused briefly at one-minute intervals to complete micro-surveys. This study area contains diverse settings, including highly built-up and green-dominant segments. Route 1 and Route 3 were predominantly grey, characterised by higher proportions of built form (building coverage = 0.36 and 0.37; vegetation coverage = 0.28 and 0.27, respectively). In contrast, Route 2 featured greater greenery (vegetation coverage = 0.42; building coverage = 0.20), serving as the green-dominant condition. Building and vegetation coverage were calculated as the proportion of pixels classified as buildings or vegetation in panoramic images, as described in Section 3.6. All routes underwent prior environmental audits by two trained researchers to ensure consistency and comparability. The route combinations were further substantiated by a pilot walk where three postgraduate students confirmed perceptual distinctions between routes, particularly the contrast between the green route and the visually similar grey-dominant routes.

3.3. *Participants*

A total of 20 healthy adult participants were recruited from the College of Design and Engineering (CDE) at the National University of Singapore (NUS). Participants were postgraduate students, aged between 22 and 30 years (M = 22.5, SD = 2.07), comprising 11 females and 9 males. Recruitment was conducted using a convenience sampling strategy through face-to-face invitations at the CDE campus, as well as advertisements circulated via social media platforms such as Telegram, WhatsApp, and WeChat. This approach was considered appropriate as the study focused on university students, and the recruited participants are representative of the target population routinely exposed to the campus environment. By recruiting postgraduate students from CDE, we ensured that participants had

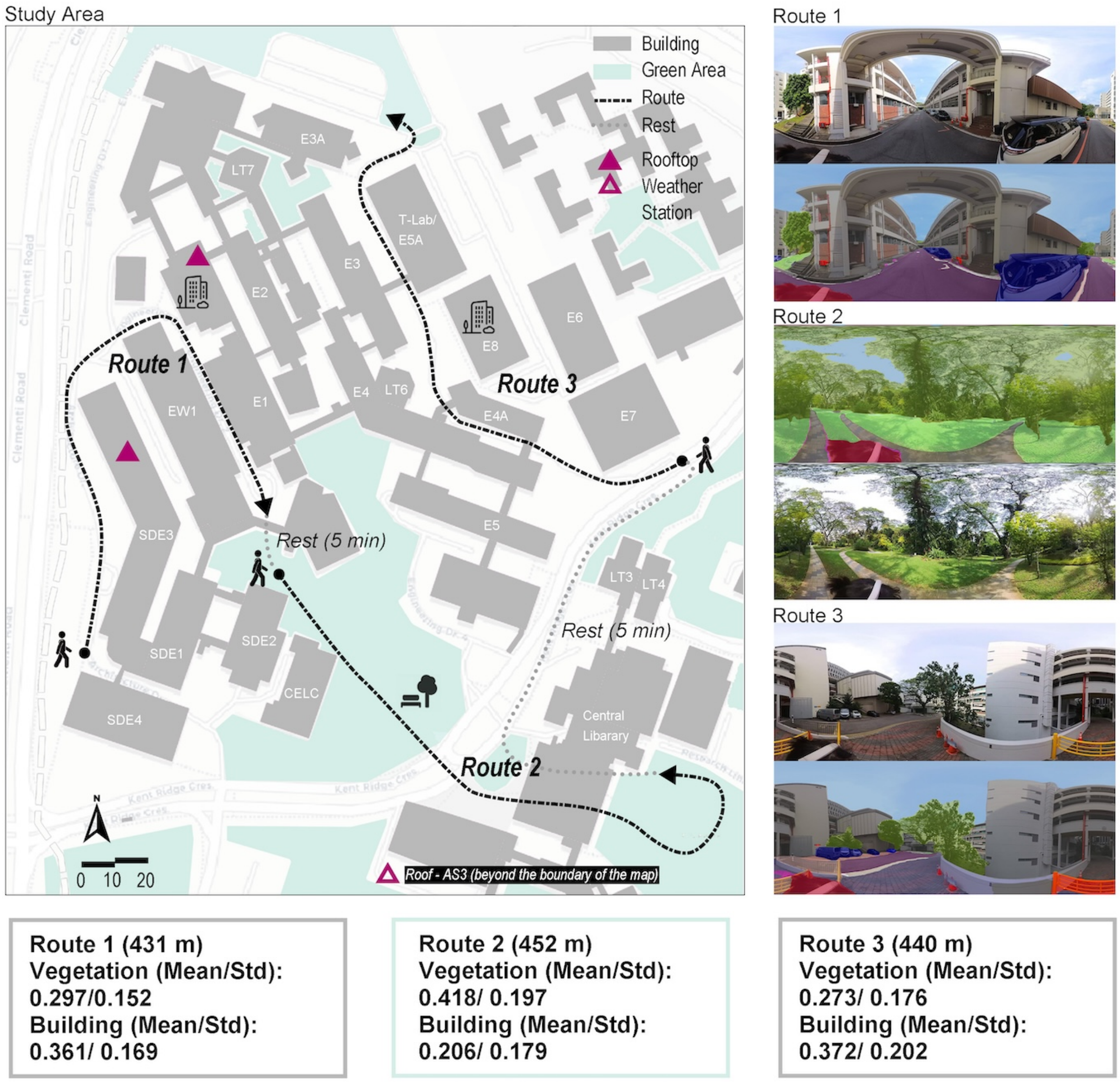

Figure 2: Three routes were selected within the College of Design and Engineering (CDE) at the National University of Singapore (NUS). Route 2 is a green-dominant route, Route 1 and 3 are grey-dominant routes. Three nearest Weather stations are indicated on the map with their respective locations. One weather station (Roof - AS3) is beyond the boundary of the map, but its approximate location is marked for reference.

a similar level of familiarity with the university environment, including the walking routes used in the study. This allowed us to better simulate the real-world exposure individuals experience in their daily routines within the university setting, providing valuable insights for campus restoration as well as everyday restorative experiences in urban environments.

All participants provided written informed consent prior to participation. The study protocol received ethical approval from the Institutional Review Board of NUS (Reference No. NUS-IRB-2024-1013). Participants received a monetary compensation upon completion of the study.

Table 1: Participant demographic and psychosocial characteristics (N = 20)

Characteristic	**Value**
Age (years), mean (SD)	22.5 (2.07)
Gender, n (%)	Female: 11 (55%), Male: 9 (45%)
Perceived Stress Score (PSS), mean (SD)	30.50 (8.15)
Noise Sensitivity, mean (SD)	6.65 (2.30)
Thermal Comfort Sensitivity, mean (SD)	6.95 (2.06)

3.4. Measures

To comprehensively evaluate participants' restorative experiences during walking, we employed a multi-dimensional assessment strategy, including physiological, perceptual, and affective outcomes of restoration.

Physiological restoration: Heart Rate Variability (HRV) was used as a physiological marker of restoration, serving as an indicator of the autonomic nervous system balance and reflecting momentary stress and recovery. HRV has been widely employed in similar studies as a reliable indicator of psychophysiological restoration and is often used to assess the physiological response (Stigsdotter et al., 2017; Jeon et al., 2021). In this study, HRV was recorded immediately before and after each walking session using Apple Watch devices and retrieved through the Cozie app (Tartarini et al., 2023).

Perceptual restoration: Two self-report instruments were used. First, the full-version *Restorative Outcome Scale* (ROS) (Hartig and Staats, 2006) was administered pre- and post-walk to assess subjective perceptions of restoration. Second, a three-item Likert scale adapted from Kajosaari and Pasanen (2021) evaluated relaxation, stress reduction, and attraction during each walk at one-minute intervals. To avoid mental pressure and fatigue during repeated measures, a short version of the ROS was also used. This version employed a 5-point Likert scale with simplified questions and an easy-to-use interface, designed to minimize cognitive load. Each question took approximately two seconds to complete, achieving good reliability (Cronbach's alpha = 0.897).

Affective restoration: The *Positive and Negative Affect Schedule* (PANAS) (Watson et al., 1988) was used to measure emotional states before and after each walking session. Positive and negative affect subscales were analysed separately and demonstrated good reliability (Table 2).

Table 2: Internal consistency (Cronbach's α) for outcome measures before and after walking

Measure	**Pre-Walking**	**Post-Walking**
Restorative Outcome Scale (ROS)	0.884	0.902
PANAS – Positive Affect Subscale	0.862	0.888
PANAS – Negative Affect Subscale	0.897	0.907

3.5. Procedure

Participants followed the three predefined walking routes in a fixed order: Route 1 (grey), Route 2 (green), and Route 3 (grey), with each individual route lasting approximately 15 minutes (5 minutes rest + 10 minutes walking). To minimize fatigue and alleviate any cumulative walking effects, participants took a 5-minute seated rest after each route to refresh before continuing. This break allowed them to recover from any physical exertion and ensured that their psychological responses were not unduly influenced by cumulative fatigue from walking consecutive routes. Each session accommodated one or two participants, walking independently.

(1) Pre-walk preparation. Participants received digital route maps and completed a short onboarding survey which aims to collect personal traits, including age, gender, perceived stress (PSS), and self-reported sensitivity to noise and thermal conditions (Table 1). To standardise fatigue levels, participants were asked to be engaged in work or study for at least 30 minutes before the walk. Experiments were conducted only under non-extreme weather conditions.

(2) Devices and instrumentation. Four devices were used to facilitate multimodal data collection throughout the walking experiment (Figure 1). An Apple Watch equipped with the Cozie app was employed to collect participants' physiological signals, including heart rate, as well as their real-time responses to micro-surveys delivered at 1-minute intervals during walking. The micro-survey feature was custom built by the research team using Cozie's configurable survey interface. Simultaneously, ambient sound levels were recorded in real time using a UT353/UT353BT digital sound level meter. A paired smartphone was used to administer the PANAS and ROS questionnaires before and after each walking session. Lastly, panoramic images of the three experimental routes were captured using an Insta360 X4 camera. These images were acquired separately from the participant sessions and later processed to extract environmental visual features.

(3) Walking session structure. Each route followed a consistent structure (Figure 3):

Pre-walk assessment. Participants completed affective and perceptual questionnaires (PANAS, ROS; see Measures) to establish baseline scores. A one-minute breathing session on the Apple Watch was used to record HRV.

Walking phase. Participants walked for 10 minutes, completing three-item micro-surveys via the Apple Watch every minute. GPS and heart rate were continuously recorded.

Post-walk assessment. Participants repeated the PANAS and ROS, and completed another HRV session.

During the walking experiment, each participant was accompanied with a research team member while walking on the sidewalk around the path. The noise meter was carried by the researcher, and the paired apple watch and smartphone were with the participant. The researcher was responsible for recording the noise level when the participant gave comfort feedback on Cozie, and did not interfere or talk with the participant unless certain instructions were needed (e.g., directing the path).

Micro-survey timestamps and GPS data were used to align feedback with environmental variables (e.g., visual features, noise levels) for subsequent data fusion.

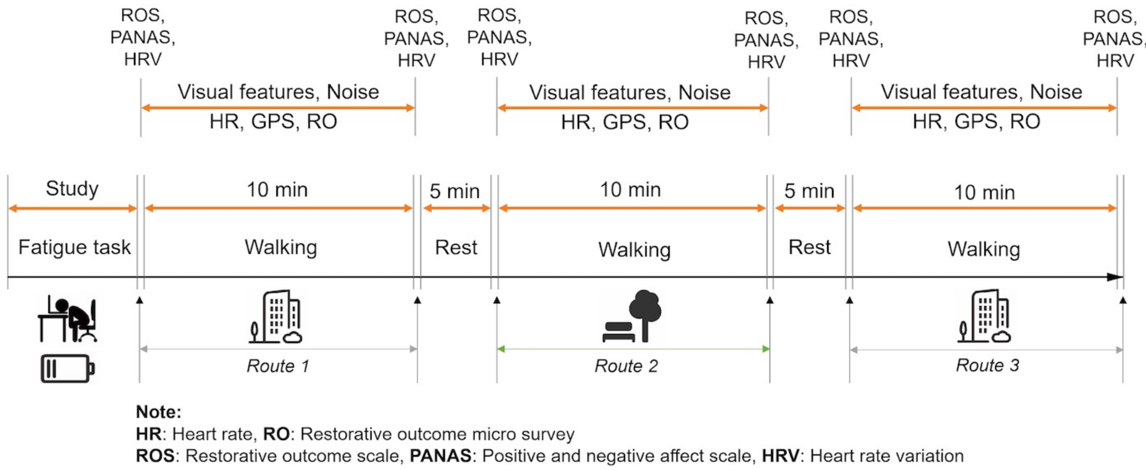

Figure 3: Experimental procedure and timeline of measurements across the three walking routes.

Figure 4: Iterative three-item restorative micro-survey delivered via Apple Watch using the Cozie app.

3.6. Environmental feature processing

To characterize the multi-sensory environment and assess its impact on participants' restorative responses, this study integrated visual, acoustic, climatic, and physiological data. These features served as explanatory variables in the subsequent modelling stages.

Visual features. On January 7, 2025, a researcher recorded continuous videos along the three walking routes and uploaded them to Mapillary. Using automatic scripts, panoramic frames were extracted from the video and associated with GPS data. A total of 500 panoramic images were retrieved from the Mapillary API, with an average interval of 2.67 meters between each frame. To capture multi-angle information, each image was processed into four directional views. Visual features were then extracted through a computer vision pipeline implemented in ZenSVI (Ito et al., 2025), which combines both high-level semantic and low-level image attributes.

Table 3: Summary of input features: model and algorithms.

CV Categories	Model	Dataset	Input features
Semantic segmentation	Mask2Former	Mapillary Vista	16
Scene depth	DepthAnything v2	-	6
Low-level features	OpenCV	-	9

High-level features included the proportion of streetscape elements (e.g., vegetation, buildings, sidewalks) detected using the Masked-attention Mask Transformer (Mask2Former), a vision transformer-based model pre-trained on the Mapillary Vista dataset (Cheng et al., 2022). Depth-related spatial structure was estimated using DepthAnything v2 (Yang et al., 2024), which computes pixel-wise scene depth from single images. Low-level image attributes—including hue, lightness, saturation, edge intensity, and blur—were extracted using the OpenCV library. The combination of high-level semantic content and low-level perceptual features enhances the model's sensitivity to environmental qualities that shape human perception (Rossetti et al., 2019).

Microclimate data. Climatic parameters, including air temperature, relative humidity, wind speed, and global horizontal irradiance (GHI), were collected from three weather stations that were positioned on building rooftops around the three walking routes. For subsequent analysis at a location on a walking route, the data from the nearest weather station was used. The weather station data were recorded at a 1-minute interval, ensuring adequate temporal resolution to match the walking experiment. In addition, the rooftop GHI from weather stations was converted to ground-level GHI that incorporates shading effects of buildings and tree canopies, using a panorama-based technique developed by (Fujiwara et al., 2024b). We simulated GHI for each panorama image at each 1-minute interval, providing a more granular solar irradiance feature for the multisensory modelling.

Acoustic data. Momentary noise levels, expressed in decibels (dB), were captured using handheld sound level meters. These values were aligned by GPS coordinates and timestamp to ensure spatial-temporal correspondence with other datasets.

Physiological data. Real-time heart rate data were collected during walking and served as a physiological proxy for momentary stress and arousal (see Section 3.5). These data were retrieved from the Cozie API with a resolution of approximately 20 seconds were processed using a min-max scaler for each individual.

All datasets were synchronised by GPS and time, and then aggregated using a spatial-temporal windowing method. Readings captured within a one-minute interval at the same location with a five-metre buffer area were averaged into a single observation. The final dataset contained 344 data points, each representing a temporally aligned snapshot of environmental and physiological conditions.

3.7. Data analysis

3.7.1. Pre-post Route differences

Data preprocessing. For psychological outcome variables—including Positive Affect (PA), Negative Affect (NA), and ROS—raw scores were retained. For physiological restoration, HRV was transformed into percentage change to normalize individual baselines:

$$\text{HRV\% Change} = \frac{\text{HRV}_{\text{post}} - \text{HRV}_{\text{pre}}}{\text{HRV}_{\text{pre}}} \times 100 \tag{1}$$

Both Route (Route 1, 2, and 3) and Time (Pre, Post) were treated as ordinal repeated-measures factors.

Within-route variation. To explore restoration changes within each route, paired-sample t-tests were performed comparing pre- and post-scores separately for PA, NA, ROS, and HRV. These analyses established whether each route induced statistically significant improvements across outcomes.

Between-route variation. For each participant, difference scores were computed to quantify the restoration gained from each route:

$$\Delta_{\text{Score}} = \text{Post}_{\text{score}} - \text{Pre}_{\text{score}} \tag{2}$$

Descriptive statistics (means, standard deviations, ranges) were calculated by route and outcome variable. One-way Analysis of Variance (ANOVA) was used to compare difference scores across routes, followed by paired t-tests for each pairwise comparison: Route 1 vs. Route 2, Route 2 vs. Route 3, and Route 1 vs. Route 3.

Covariate effects and linear mixed modelling. To account for inter-individual variability and to examine the influence of personal characteristics, linear mixed models (LMMs) were constructed. This method allows for the inclusion of participant ID as a random effect, thereby controlling for within-subject correlations. Each outcome variable (PA, NA, ROS, HRV%) was modeled using LMMs with participant ID as a random effect. Fixed effects included Route, Time (Pre/Post), their interaction, and participant-level covariates: gender, perceived stress (PSS), noise sensitivity, and thermal comfort sensitivity.

$$Y_{ij} = \beta_0 + \beta_1 \cdot \text{Route}_j + \beta_2 \cdot \text{Time}_i + \beta_3 \cdot (\text{Route}_j \times \text{Time}_i) + \sum_k \gamma_k \cdot \text{Covariate}_k + u_i + \epsilon_{ij} \tag{3}$$

where u_i represents the random intercept for participant i, and ϵ_{ij} is the residual error.

Effect size estimation. To further quantify route-level effects, estimated marginal means (EMMs) were calculated from the LMMs using post-estimation tools. EMMs represent the model-adjusted means for each Route × Time combination, controlling for covariates. These adjusted scores provide standardised comparisons of restorative benefits across routes, visualised with 95% confidence intervals.

3.7.2. Machine learning model construction

To capture the non-linear relationships between multi-sensory environmental features and perceived restoration at the micro level, we formulated the task as a binary classification problem. This framing was chosen because the perceptual restoration scores are ordinal and skewed, making direct regression less reliable, while classification allows for clearer label separation and more robust interpretability through explainable AI methods (Lei et al., 2025; Liu et al., 2023). Labels for three restoration perceptions (i.e. relaxation, stress reduction, and attraction) were discretised into two classes: low (0) and high (1). To sharpen label contrast and reduce ambiguity, the middle 20% of the data (centred around the median) was removed, following an approach commonly used in perceptual and affective computing research to improve classification reliability (e.g., (Zhang et al., 2018)).

Input features. The features used for classification included 31 visual variables, as described in Section 3.6 and detailed in Table 3, as well as microclimate data, noise levels, and real-time physiological responses. A full summary of all environmental and physiological features is provided in Table 4.

Table 4: Full list of input features used in the ML models.

Feature Type	**Variables**
Microclimate	Air temperature, Relative humidity, Wind speed, Global Horizontal Irradiance (GHI)
Acoustic	Noise level (dB)
Physiological	Real-time heart rate
Visual	Semantic segmentation (16), Scene depth (6), Low-level features (9)

Model training and validation. The final dataset (344 observations) was randomly split into 60% for training and 40% for testing. XGBoost was used as the classification model for all restorative perceptions for its strong performance and interpretability in urban perception and environmental behaviour research (Zhang et al., 2018). Model hyper-parameters were optimised using 5-fold cross-validation with randomised search to improve generalisability. The selected models were then used in subsequent explainability analysis to examine feature contributions.

3.7.3. Association at location level using XAI

To interpret the contribution of environmental features to predicted restoration outcomes, we applied Explainable Artificial Intelligence (XAI) techniques to interpret the best-performing machine learning models (Ali et al., 2023). SHapley Additive exPlanations (SHAP) were used on the trained XGBoost models. SHAP attributes a contribution value to each feature for a given prediction, enabling both local and global interpretation of model behaviour (Lundberg and Lee, 2017).

The SHAP framework approximates the model output $g(z)$ as:

$$g(z) = \phi_0 + \sum_{j=1}^{M} \phi_j z_j \tag{4}$$

where ϕ_0 is the expected model output (base value), ϕ_j is the SHAP value for feature j, and z_j is the feature's value.

SHAP values were computed using the TreeExplainer module in the SHAP Python package (version 0.46.0). We focused the interpretation on predictions labelled as Class 1, representing high levels of restoration. Global SHAP importance values were calculated to identify the most influential features across three restorative outcomes: relaxation, stress reduction, and attraction.

For each model, the top five features with the highest and lowest SHAP contributions were extracted across six categories: (1) semantic segmentation, (2) scene depth, (3) low-level visual features, (4) microclimate, (5) noise, and (6) momentary heart rate. To visualise these contributions, we generated category-wise bar plots showing directional importance for each outcome.

In addition, to enable high-level comparison across feature domains, we aggregated the SHAP contributions for each category and visualised their total influence in a summary bar chart. These visualisations highlight how multi-sensory environmental characteristics influence the perception of restoration at the location level.

3.7.4. Scenario improvement

To explore how strategic design interventions might enhance perceived restoration in urban environments, we developed a simulation pipeline that integrates visual improvement strategies with predictive modelling.

Visual upgrading strategies. Based on the results of the explainable machine learning analysis, several visual enhancement strategies were proposed to target features most strongly associated with high restorative perceptions. These strategies were operationalized through controlled image generation using GPT-4o, a multimodal generative model. Original street-view perspective images were provided as input, along with tailored prompts reflecting each upgrading strategy (e.g., increasing greenery, removing vehicles, adding signage). To preserve the spatial realism of the scenes, the model was constrained to make minimal alterations to unrelated elements, maintaining the same viewing angle, perspective, and scale as the original image.

Feature re-extraction. The upgraded images were then processed using the same computer vision pipeline (detailed in Section 3.6) to extract a new set of visual features, ensuring consistency in feature engineering across original and modified scenarios.

Predictive evaluation. The updated feature vectors were subsequently fed into the best performing classification models (Section 3.7.2) to obtain predicted probabilities of perceived restoration. These probability scores were directly compared to those of the original scenarios to assess the relative effectiveness of each upgrading strategy.

4. Results and analysis

4.1. Route differences on pre-post quasi experiment

4.1.1. Pre-post differences for each route

The pre- and post-walking differences in restorative outcomes were examined separately for each route using paired-sample t-tests. Table 5 summarises the t-statistics, Cohen's d, and associated p-values for Positive Affect, Negative Affect, Restorative Outcomes, and HRV (%).

Table 5: Pre-post differences for each route: t-statistics, Cohen's d, and p-values.

	Positive Affect	**Negative Affect**	**Restorative Outcome**	**HRV (%)**
R1				
t-statistic	-0.878	0.501	-1.091	-1.804
Cohen's d	-0.207	0.118	-0.257	-0.425
p-value	0.392	0.679	0.290	0.089
R2				
t-statistic	1.494	-0.625	3.144	1.186
Cohen's d	0.352	-0.147	0.741	0.280
p-value	0.153	0.540	0.006*	0.252
R3				
t-statistic	0.240	-1.275	0.831	0.895
Cohen's d	0.055	-0.293	0.191	0.205
p-value	0.813	0.219	0.417	0.382

Across routes, general trends were observed in pre-post changes. Route 1 showed small declines in Positive Affect, Restorative Outcome, and HRV (%), though none were statistically significant. Route 2 demonstrated a significant improvement in Restorative Outcome ($d = 0.741$, $p = 0.006$), with positive trends also found for Positive Affect and HRV (%). For Route 3, while overall changes were slight, a moderate reduction in Negative Affect ($d = -0.293$) was observed.

4.1.2. Changes in restoration across routes

To compare restoration changes across different environmental exposures, difference scores for four restorative parameters—positive affect (PA), negative affect (NA), restorative outcome (ROS), and HRV (%)—were calculated. Descriptive statistics are presented in Table 6. Among the three routes, Route 2 (green-dominated) yielded the most substantial improvements across affective, perceptual, and physiological dimensions. In contrast, Route 1 (grey-dominated) consistently exhibited the least favourable outcomes, with negative mean changes across all parameters. Notably, the largest variability was observed for HRV (%) changes, indicating considerable individual differences in physiological responses.

Table 6: Descriptive statistics of difference scores (Post–Pre) for each route.

	Positive Affect	**Negative Affect**	**Restorative Outcome**	**HRV (%)**
Route 1 (Mean)	-1.222	0.500	-2.389	-6.867
Route 1 (SD)	4.558	2.792	10.634	24.272
Route 2 (Mean)	1.833	-0.611	5.889	20.341
Route 2 (SD)	3.536	3.346	5.487	39.067
Route 3 (Mean)	0.263	-1.263	1.368	15.492
Route 3 (SD)	2.469	3.798	6.792	27.752

ANOVA results (Table 7) revealed significant differences among the three routes for Positive Affect (p = 0.026), Restorative Outcome (p = 0.009), and HRV (%) (p = 0.019), whereas differences in Negative Affect were not statistically significant (p = 0.156).

Pairwise comparisons (Table 7) and visualisation (Figure 5) further revealed that Positive Affect, Restorative Outcomes and HRV significantly improved after exposure to Route 2 compared to Route 1. The results indicate a significant restorative benefit by walking in green environment. Although slight decreases were observed when transitioning from Route 2 to Route 3, restorative benefits remained higher than baseline (Route 1) levels. HRV (%) improvements were significantly greater after Routes 2 and 3 than after Route 1, suggesting sustained physiological restoration after green exposure. Negative Affect showed a continuous decrease after Route 2, with the reduction becoming more pronounced after Route 3, although changes were marginally significant.

Overall, the results highlight the preliminary evidences that exposure to greener environments yielded notable restorative benefits, which partially persisted even after returning to built-dominated settings.

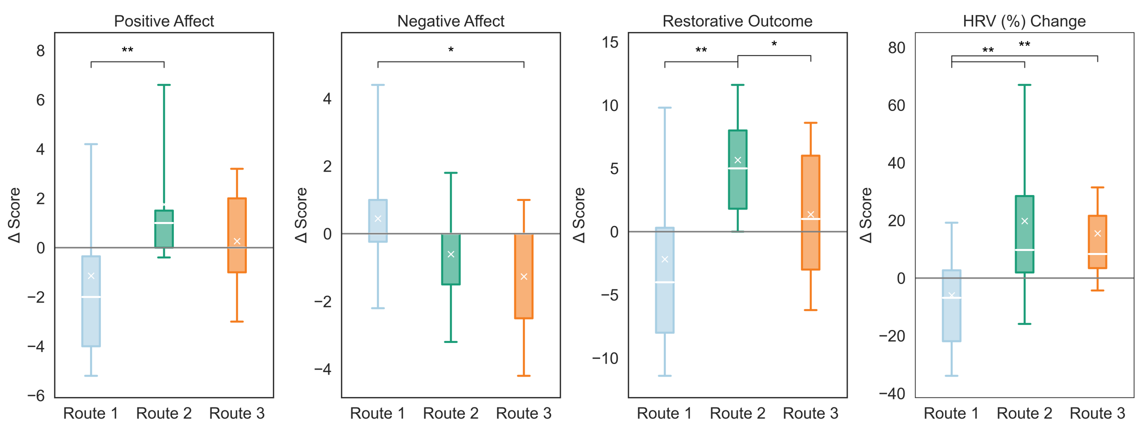

Figure 5: Box plots of difference scores in Positive Affect, Negative Affect, Restorative Outcome, and HRV (%) across Route 1, 2, and 3.

Table 7: ANOVA and pairwise t-test results for difference scores across routes.

	Positive Affect	**Negative Affect**	**Restorative Outcome**	**HRV (%)**
ANOVA F	4.031	1.961	5.327	4.429
ANOVA p	0.026	0.156	0.009	0.019
R1 vs R2 t	-2.740	1.409	-3.036	-2.569
R1 vs R2 p	0.013	0.176	0.007	0.019
R2 vs R3 t	1.552	0.432	2.022	0.543
R2 vs R3 p	0.138	0.671	0.058	0.594
R1 vs R3 t	-1.355	2.273	-1.426	-2.717
R1 vs R3 p	0.192	0.035	0.171	0.014

4.1.3. Covariates analysis in restorative changes

To further examine how individual background characteristics influence restorative changes, in addition to the effect of environmental exposure sequences, Linear Mixed Models (LMMs) were constructed for each restorative outcome. A summary of covariate effects is presented in Table 8.

Perceived stress level and sensitivity to noise were found to be negatively associated with restorative outcomes, suggesting that general mental health status and auditory sensitivity may moderate the degree of perceived restoration benefits. Sensitivity to thermal environment was negatively associated with HRV (%), indicating that individuals more sensitive to thermal discomfort exhibited attenuated physiological restoration during walking. Additionally, male participants exhibited a positive association with changes in Negative Affect, suggesting that males tended to experience greater increases in negative emotions during walking compared to females under similar environmental exposures.

Table 8: Covariate effects on restoration outcomes (coefficients from LMMs). Asterisks (*) denote significance at $p < 0.05$. PA: Positive Affect; NA: Negative Affect; ROS: Restorative Outcome Scale.

Covariates	**PA**	**NA**	**ROS**	**HRV (%)**
Perceived stress level	0.148	0.179	0.296*	0.500
Noise sensitivity	-0.371	0.026	-1.390*	1.291
Thermal sensitivity	-0.279	-0.112	-0.763	-3.767*
Gender (male)	0.732	3.185*	-3.162	0.885

4.1.4. Effect size of restorative changes

Estimated Marginal Means (EMMs) derived from Linear Mixed Models (Figure 6) were used to assess model-adjusted restoration changes across routes. Table 9 summarises the EMM values for each restorative outcome.

Route 2 (green route) consistently exhibited the highest EMM values across Positive Affect (ΔEMM = 1.69), Restorative Outcome (ΔEMM = 5.21), and HRV (% change;

Table 9: Estimated Marginal Means (EMMs) of restoration outcomes across routes.

Outcome	Route 1	Route 2	Route 3
Positive Affect	-1.145	1.690	0.263
Negative Affect	0.499	-0.722	-1.263
Restorative Outcome	-2.251	5.209	1.368
HRV (%) Change	-4.324	6.822	3.840

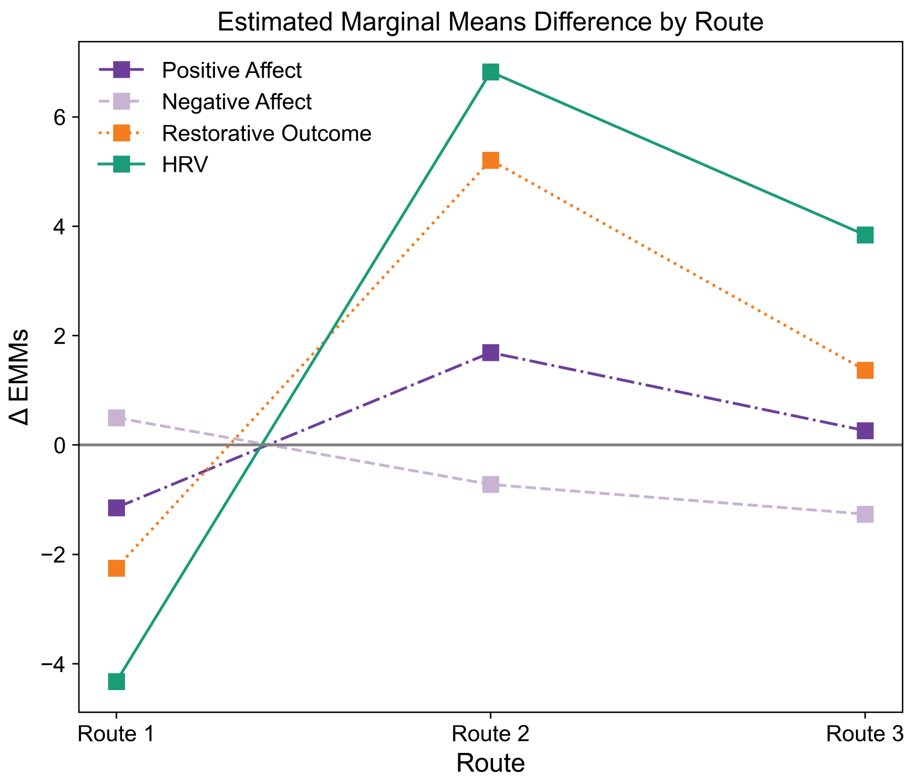

Figure 6: The differences of estimated marginal mean of restoration variables changes across 3 routes.

ΔEMM = 6.82), indicating substantial model-estimated improvements following green exposure. In contrast, Route 1 (grey route) showed negative EMMs across all outcomes, reflecting limited or adverse effects on restoration.

After controlling for individual background characteristics, positive EMM values were still observed during Route 3 across Positive Affect (ΔEMM = 0.26), Restorative Outcome (ΔEMM = 1.37), and HRV (% change; ΔEMM = 3.84). Notably, HRV remained substantially higher than baseline levels, suggesting that the physiological restorative effects gained from the green exposure (Route 2) persisted even when participants subsequently walked through built-oriented environments. This finding highlights the potential for transient green exposures to yield lasting physiological benefits beyond the immediate setting.

Comparative trends across outcomes revealed that HRV changes exhibited the largest

EMM shifts across routes, followed by Restorative Outcomes and Positive Affect. Negative Affect displayed an inverse trend, decreasing after exposure to greener environments. These findings suggest that greener environments have the strongest positive impact on physiological restoration, followed by perceptual and affective benefits.

4.2. Association between multisensory urban environment and restoration perceptions

4.2.1. Models evaluation

The XGBoost models demonstrated good performance in predicting restoration perceptions (i.e. Relaxation, Stress Reduction, and Attraction), with accuracy scores ranging from 0.8375 to 0.8987 and weighted F1 scores between 0.84 and 0.90 (Table 10). These results indicate acceptable model validity for subsequent explainability analysis.

Table 10: Model performance metrics for restoration perception prediction.

Model	Accuracy	Precision	Recall	Weighted Avg F1
Relaxation	0.883	0.885	0.885	0.880
Stress Reduction	0.899	0.900	0.900	0.900
Attraction	0.836	0.845	0.840	0.840

4.2.2. Environmental features contribution

The contribution of multisensory environmental features to restorative perceptions was analysed using SHAP interpretation (Figure 8). The top five positive and negative contributing features across six feature categories were identified for each restorative dimension. Further, Figure 7 summarises the aggregated contribution of each feature category.

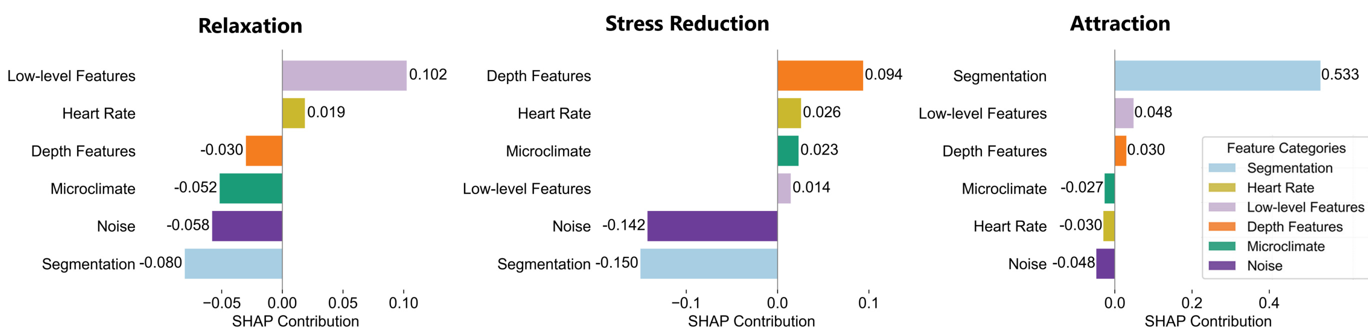

Figure 7: The aggregated feature importance of varied feature categories across visual elements, low-level features, scene depth, micro-climate, noise, and heart rate

Across all outcomes — Relaxation, Stress Reduction, and Attraction—visual features emerged as the most influential predictors, followed by noise and microclimate variables. Within visual features, semantic segmentation indices contributed positively to higher perceived relaxation (+0.102) and attraction (+0.533), supporting the Prospect-Refuge Theory, which posits that environments offering clear spatial organisation and semi-open settings enhance feelings of safety and comfort (Appleton, 1975). Interestingly, scene depth features negatively contributed to relaxation (-0.030) but positively associated with stress reduction (+0.094) and attraction (+0.030). The statistical results suggests that while spatial complexity may hinder immediate psychological relief, it simultaneously offers stimulating environments that reduce boredom and increase engagement.

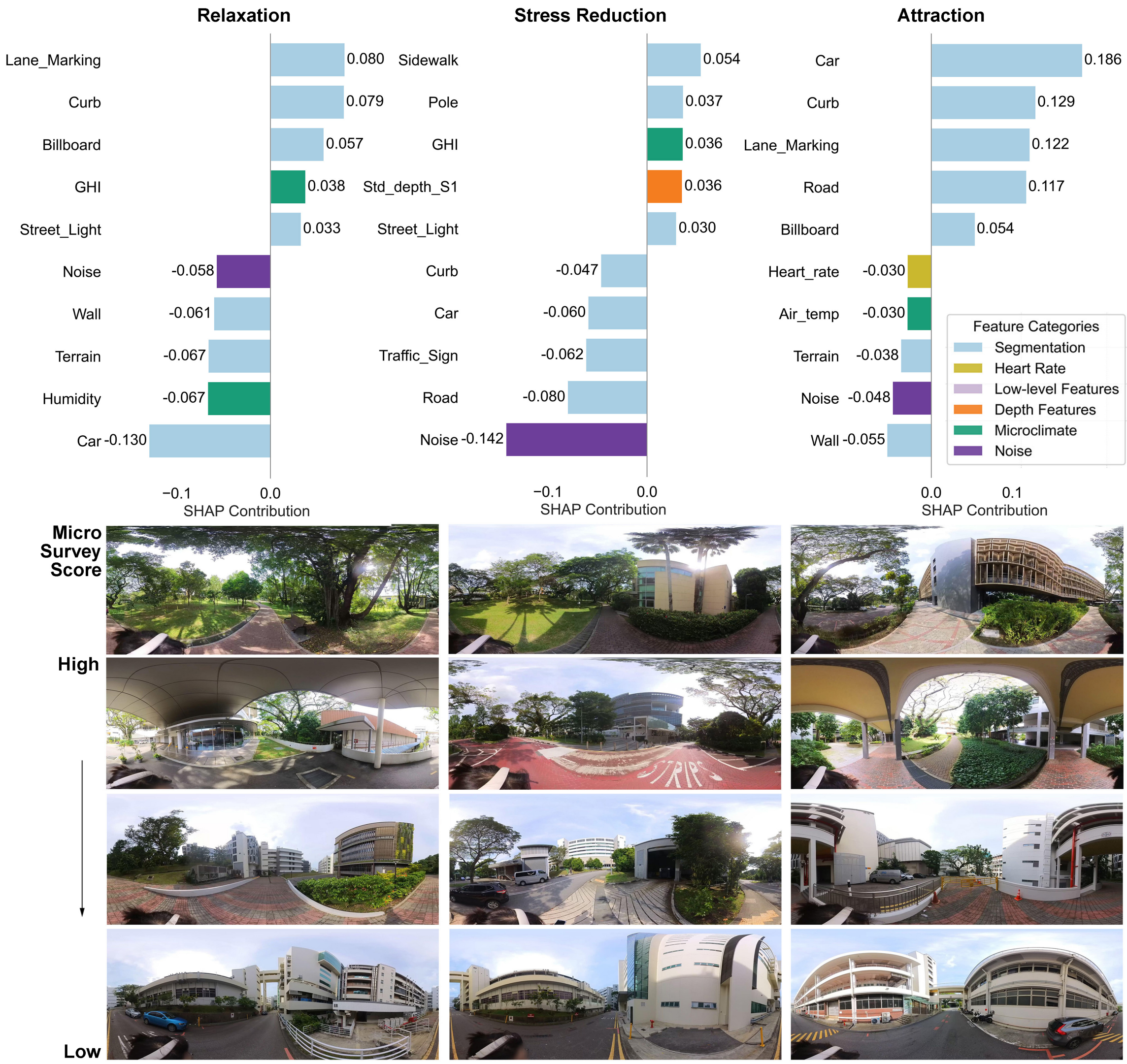

Figure 8: The top 5 features with highest positive and negative contribution to predicting the high restoration level.

A closer examination of specific features revealed consistent patterns across restorative outcomes. At the object level, walkability elements (e.g. sidewalks and lane markings) had consistent positive effects across all outcomes (e.g., +0.080 for lane markings on Relaxation), while cars (-0.130 for Relaxation) and roads (-0.080 for Stress Reduction) ranked among the strongest negative contributors, reflecting sensory overload or perceived danger. Interestingly, billboards showed a small yet positive contribution to Relaxation (+0.057) and Attraction (+0.054), possibly reflecting urban visual interest and signalling maintenance or care. Among low-level visual features, brightness and hue positively influenced Relaxation (+0.102) and Attraction (+0.048), consistent with previous studies linking colour vibrancy and natural light exposure to emotional uplift.

Notably, noise consistently emerged as a top negative contributor across all restoration outcomes, underscoring its detrimental impact on perceived environmental quality. It ranked among the five most influential negative features in all three models. For Stress Reduction, noise was the single most impactful negative predictor, with a SHAP value of -0.142 — indicating a substantial reduction in perceived stress relief in noisier environments. Similarly, for Attraction, noise was the second most detrimental factor (-0.048). This finding underscores the fundamental and dominant role of acoustic comfort in promoting perceived restoration, echoing the importance of soundscapes in shaping quality of life.

Microclimatic indicators also played a meaningful role. Humidity and air temperature had negative contributions across Relaxation (-0.067) and Attraction (-0.030), indicating that thermal discomfort can dampen the psychological benefits of walking. Conversely, solar irradiance (measured by GHI) contributed positively to Stress Reduction (+0.036) and Relaxation (+0.038), suggesting that moderate sunlight exposure may enhance environmental restorative potential.

In summary, the results suggest that a quiet, open, and walkable environment, enriched by moderate visual stimulation, thermal comfort, and access to natural light, fosters a psychologically supportive walking experience. This study found that such environments facilitate relaxation, stress relief, and engagement without inducing sensory overload, providing empirical support for designing more restorative everyday urban spaces.

4.3. Scenario improvement

Based on the feature contribution analysis, the top contributors were used to guide scenario improvements. Noise, as the strongest negative factor, was implemented as a standalone acoustic intervention. In contrast, the main visual features (lane markings, curbs, billboards, cars, and walls) were combined into an integrated visual strategy, since such elements are typically introduced together in practice (e.g., pavement markings and curbs to improve walkability, billboards or signage with reduced monotonous walls to enhance visual interest). To further align with established design practice, additional greenery was also incorporated into the visual package, despite not being ranked among the top features in the machine learning model, given its consistently demonstrated restorative benefits in the literature (Kaplan and Kaplan, 1989; Zhang et al., 2025; Li et al., 2023; Pazhouhanfar and M.S., 2014; Brown et al., 2013a). Taken together, these design updates were intended to simulate realistic intervention strategies, rather than isolated feature changes, providing a pipeline from model interpretation to applicable urban design improvements.

Based on the above considerations, three design improvement strategies were tested on scenarios with initially low restoration ratings (Figure 9):

- Scenario 1 focused on acoustic enhancement by reducing the ambient noise level from 72.1 dB to 58 dB.
- Scenario 2 targeted visual improvements, including the addition of pavement markings, billboards, and trees, as well as the removal of obstructive elements such as parked motorcycles.
- Scenario 3 combined both visual and acoustic interventions to simultaneously address multisensory environmental qualities.

The upgraded scenarios were subsequently re-evaluated by inputting the modified environmental features into the trained machine learning models. The predicted probabilities of achieving higher restoration levels across the dimensions of Relaxation, Attraction, and Stress Reduction were compared between original and upgraded conditions (Figure 10). Overall, all three strategies led to improvements in predicted restoration outcomes. Specifically, the combined visual and acoustic upgrade (Scenario 3) demonstrated the greatest enhancement for relaxation outcomes, suggesting that multi-sensory interventions exert synergistic benefits for psychological relief. Improvements in perceived attraction were observed across all scenarios, with comparable magnitudes, indicating that either visual or acoustic enhancements alone could substantially boost environmental appeal. Notably, for stress reduction, the reduction in noise levels alone (Scenario 1) was the most effective strategy, highlighting the dominant role of acoustic environments in mitigating perceived stress during walking.

These results underscore the importance of multi-sensory considerations in urban design for promoting everyday restoration. While acoustic quality improvements appear especially critical for reducing stress, integrating visual enhancements can further elevate relaxation and attraction experiences, supporting the creation of psychologically supportive pedestrian environments.

5. Discussion

This research builds on previous studies of restorative environments and environmental psychology, but extends this work by employing a real-world, quasi-experimental walking study that captures momentary physiological, perceptual, and affective responses across sequential exposures to green and grey environments. These innovations were harnessed to overcome key limitations in the literature, including the reliance on static imagery or simulated settings, the under-exploration of multisensory features beyond the visual domain, and the lack of empirical testing of exposure sequences in everyday contexts. Beyond these conceptual contributions, this study also offers a high-resolution, time-based methodological framework that integrates multimodal environmental sensing, ecological momentary assessment (EMA), and physiological monitoring with machine learning, XAI, and generative LLM. This approach provides quantitative, finer-grained insights into human-environment interactions and restoration during walking activities, and offers a pipeline for evidence-based scenario improvements.

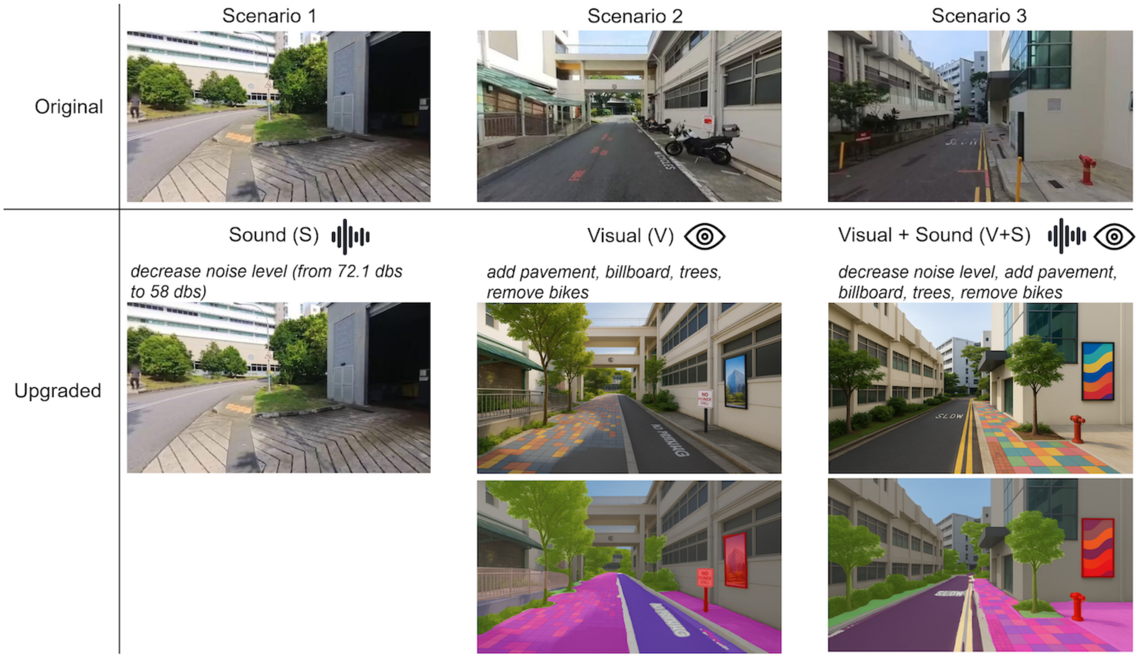

Figure 9: Upgrading strategies for three scenarios initially associated with low restoration perceptions. Visual improvements were generated using GPT-4o to simulate realistic environmental upgrades.

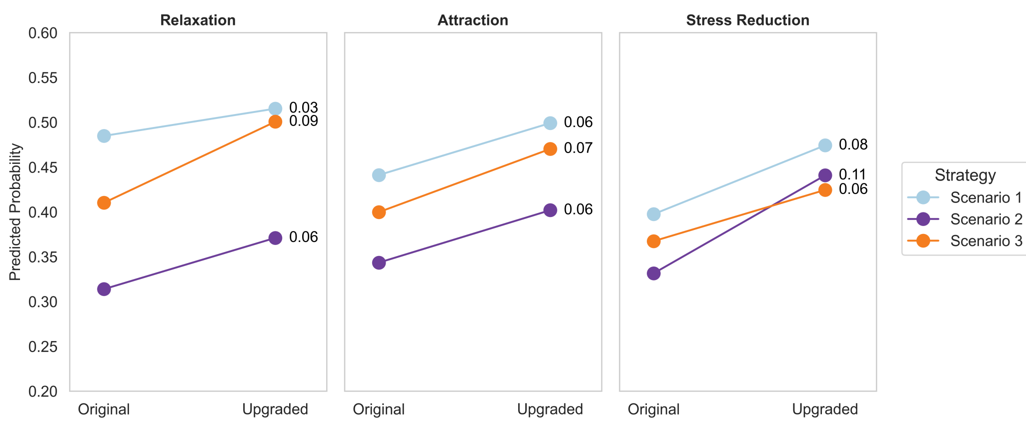

Figure 10: Predicted probability changes in restoration outcomes (Relaxation, Attraction, Stress Reduction) before and after scenario upgrades. Scenario 1: Sound improvement; Scenario 2: Visual improvement; Scenario 3: Combined sound + visual improvement.

It was our ultimate goal to assess whether green exposure confers lingering restorative benefits when individuals are subsequently re-exposed to built-dominated spaces, and to disentangle how visual, acoustic, and microclimatic factors interactively influence momentary restoration. Unlike previous studies relying on simulated stimuli or isolated features, our real-world approach provides direct empirical evidence that supports earlier lab-based findings—confirming that brief exposure to greenery can produce lingering restorative benefits, even when followed by built-dominated environments. Beyond this empirical confirmation, our study advances the literature by offering a more finer-grained understanding of the relative influence of multisensory environmental factors on restoration. Our results expand earlier theories suggesting that environmental stimuli, including noise, thermal discomfort, and visual complexity can either support mental relaxation or exacerbate stress (Jiang et al., 2025; Lindal and Hartig, 2013; Xie et al., 2022). In contrast, certain designed visual features—including sidewalks, signage, and street lighting—were positively associated with restoration, highlighting that well-maintained built elements can play a supportive role alongside natural features in enhancing momentary psychological benefit (Lei et al., 2025; Bai and Jin, 2023; Liu et al., 2023). While our study's contributions aimed to advance methodological approaches in neurourbanism, they also demonstrate practical value for urban design by identifying key multisensory factors—such as greenery, noise levels, and microclimatic comfort—that enhance or hinder restorative experiences during everyday walking. These insights offer actionable guidance for designing psychologically supportive urban environments.

5.1. Sequential exposure: lasting benefits of green environments

This study extends laboratory research on the "inoculation effect" of nature by demonstrating its presence in real-world walking contexts. Whereas previous experiments used controlled stimuli (e.g., videos or VR) followed by artificial stressors (e.g., math tasks) (Parsons et al., 1998; Brown et al., 2013b), our quasi-experimental design shows that even brief exposure to greenery during walking can sustain restorative benefits when individuals subsequently encounter built-dominated environments.

According to ART and SRT, exposure to restorative environments helps individuals recover from cognitive fatigue, restore attentional capacity (Kaplan and Kaplan, 1989; Kaplan, 1995), and reduce stress while evoking positive affect and increasing arousal (Ulrich, 1984). Our study not only aligns with this theoretical framework—demonstrating through pre-post evaluations that natural environments provide significant cognitive, affective, and physiological benefits—but also expands on it by showing that the restored attention capacity gained from green pre-exposure can last beyond the initial exposure, acting as a buffer against fatigue. Specifically, participants exhibited continued improvements in restorative outcomes and heart rate variability (HRV) after transitioning from a green route (Route 2) to a grey route (Route 3), relative to baseline measurements. Elevated HRV after green exposure aligns with studies showing nature's ability to promote parasympathetic activity and physiological recovery (Jeon et al., 2023; Asim et al., 2023). This suggests that prior green exposure primes the psychophysiological system, enhancing resilience to less supportive urban environments. The effect was most evident in HRV. These findings indicate that physiological stress reduction via parasympathetic activation from green exposure helps individuals better cope with subsequent urban stressors, providing a lasting psychophysiological buffer against the demands of everyday urban life. This suggests that even short walking breaks in green-rich environments, such as those surrounding offices or university campuses, may help individuals recover from mental fatigue more efficiently and enhance both well-being and productivity in everyday life.

5.2. Multisensory environments: integrating visual, auditory, and climatic influences

Our findings underscore the importance of multisensory urban stimuli in shaping momentary restoration. While visual elements remain the dominant contributors which are widely supported in prior research (Zhang et al., 2024b,c; Subiza-Pérez et al., 2021), this study offers a more comprehensive view by highlighting how auditory and microclimatic factors co-influence perceived restoration in real-world walking environments.

Among all features, environmental noise emerged as the most consistently negative contributor across all three restoration outcomes, particularly stress reduction. This aligns with previous studies showing that urban noise, especially from traffic and human activity, can diminish perceived restorativeness, even in otherwise green or well-designed settings (Uebel et al., 2021; Guo et al., 2022). (Payne and Bruce, 2019) found that similar noise levels neutralised restorative differences between parks and urban squares, reinforcing that noise may overshadow visual or thermal benefits. Our findings extend this perspective by showing that even in short walking episodes, elevated noise levels consistently suppress perceived relaxation and stress relief—regardless of the visual quality of the surroundings. This highlights how sound acts as a prerequisite for restoration: if the acoustic environment is poor, other sensory benefits may struggle to take effect (Bornioli and Subiza-Pérez, 2023). This supports the theoretical framework of SRT, which propose that noise, as an environmental stressor, can harm psychological responses and hinder restorative potential in urban environments (Ulrich, 1984).

Visual features, however, still play a central role. Beyond greenery, our explainable machine learning model identified several artificial elements (e.g. sidewalks, poles, billboards, and street lights) as positively associated with restorative perceptions. This supports emerging theories that built features can offer psychological benefits by enhancing environmental legibility, walkability, and perceived safety (Ewing and Handy, 2009; Shin and Woo, 2024). These features may indicate that the environment is well-maintained and socially inviting, which in turn fosters a greater sense of calm, safety, and psychological comfort. Interestingly, our pedestrian-perspective findings diverge from previous studies using street-view imagery from vehicle-mounted cameras (Wu et al., 2024), which reported negative associations for similar features. This contrast may reflect the importance of perspective: elements like sidewalks and lighting may feel supportive when directly experienced by walkers but appear as visual noise from a distant or vehicle-based view. It also underscores how environmental effects are deeply context-dependent and shaped by the sensory mode of engagement.

Scene depth, often linked to spatial complexity and visual intrigue, also showed positive contributions. This finding resonates with psycho-environmental theories that emphasize the restorative value of mystery and exploration potential (Pazhouhanfar and M.S., 2014; Subiza-Pérez et al., 2021). Our study adds to the literature by demonstrating that scene depth is not only perceptually restorative but also linked to momentary psychological benefits during active walking, aligning with ART and prospect-refuge theory, which suggest that environments that offer opportunities for exploration and a sense of security promote restoration and psychological well-being (Kaplan, 1995; Herzog and Kaplan, 1998).

In relation to climatic features, solar irradiance showed modest positive contributions to restoration, while air temperature and humidity were negatively associated with perceived benefits. These results are consistent with comfort studies suggesting that moderate sunlight enhances mood and alertness, but excessive heat or humidity can dampen well-being (Xi et al., 2012; Liu et al., 2023). Our findings highlight that even subtle thermal variations along walking routes may shape psychological responses, underscoring the need to consider microclimate in urban design for supporting mental well-being.

5.3. Design and policy implications

The findings from this study offer actionable insights for urban planning and design aimed at improving psychological well-being through multisensory strategies. Most notably, the observed inoculation effect of green exposure underscores the potential for strategic spatial configuration of greenery, rather than solely increasing its total quantity. While adding green spaces is often costly and space-limited, positioning natural elements early along walking routes — such as in the first or last mile near residential, educational, or commercial areas — could yield prolonged restorative benefits, enhancing resilience throughout subsequent urban exposures. The implications suggest a shift toward sequencing-based planning, optimising the placement of green interventions along pedestrian networks for maximum psychological return. In parallel, the explainable machine learning analysis revealed that auditory and thermal environments often rival or surpass visual features in shaping momentary restoration — particularly for stress reduction. This insight is critical: it implies that non-visual interventions (e.g., noise abatement, thermal comfort design) may offer cost-effective, high-impact strategies for enhancing environmental quality. Our scenario optimisation analysis further confirmed that reducing noise levels or combining sound and visual enhancements was most effective in improving perceived relaxation.

Together, these findings advocate for a multisensory approach to urban design, where greenery, acoustic comfort, and microclimatic regulation are integrated holistically. Urban policy should move beyond aesthetics alone and embrace sensory comfort as a foundation for promoting mental health in everyday spaces.

5.4. Limitations and future work

This study has several limitations. First, the experiment was conducted within a single university campus, which, while containing mixed-use functions, may not capture the diversity of broader urban contexts. Future studies should test this framework in more heterogeneous environments. Second, the sample size (n = 20) was constrained by logistical factors. Although comparable to other walking experiments (Myin-Germeys and Kuppens, 2021; Liu et al., 2023; Chrisinger and King, 2018; Torku et al., 2021), this limits statistical power and generalisability. Larger and more diverse samples are needed to account for background factors such as urban–rural upbringing or nature orientation. Third, physiological data collection was limited by the resolution of the Apple Watch. HRV was only available in a pre–post design, while heart rate was used for higher-resolution modelling. Measures such as EDA (Zhang et al., 2025) or continuous HRV (Jeon et al., 2023), which are not available on the device used, could provide finer-grained insights in future studies. Fourth, the fixed walking sequence may introduce order effects, even though rest periods were included to reduce fatigue. Counterbalanced designs or neutral control conditions (e.g., gym walking) should be considered in future work. Finally, the optimisation analysis was based on simulated interventions rather than real-world implementation. Future studies should validate these strategies in practice through field-based interventions and longitudinal assessments.

6. Conclusion

This study investigated how real-world exposure to multisensory urban environments — particularly the sequence of green and grey spaces — influences momentary restoration across affective, perceptual, and physiological dimensions. By combining a quasi-experimental walking protocol with momentary perception monitoring, wearable sensing, and explainable machine learning, we offer new insights into everyday restorative processes. The key findings are as follows: (1) Brief exposure to green environments offers lasting restorative benefits, even when followed by walking in built-dominated spaces, confirming a real-world inoculation effect; (2) Among multisensory environmental features, noise emerged as the most consistent negative contributor to restoration, while visual elements — such as greenery, sidewalks, and lighting — tended to support positive restorative perceptions, whereas features like parked vehicles or visual clutter showed negative associations; (3) Microclimatic variables such as temperature and humidity negatively affected comfort and restoration, while moderate solar exposure supported psychological benefits.

These findings substantiate the benefits of an integrated approach to be integrated into psychological supportive urban planning and decision making, facilitating the evidence-based and human-centric design optimisation in dense urban environment. Practically, our findings offers strategic guidance for urban planners and designers — such as prioritising early-stage greenery along walking routes and minimising noise exposure through targeted interventions. Future work may consider extending this approach to more diverse populations and city contexts, helping cities become more psychologically supportive, inclusive, and liveable.

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Author contributions

Sifan Cheng: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Visualization, Project administration. Binyu Lei: Methodology, Data Curation, Writing - Original Draft, Writing - Review & Editing. Kunihiko Fujiwara: Data Curation, Formal analysis, Writing - Review & Editing. Clayton Miller: Resources, Writing - Review & Editing. Filip Biljecki: Conceptualization, Resources, Writing - Review & Editing, Supervision, Funding acquisition. Jeroen van Ameijde: Conceptualization, Resources, Writing - Review & Editing, Supervision, Funding acquisition.

References

Ali, S., Abuhmed, T., El-Sappagh, S., Muhammad, K., Alonso-Moral, J. M., Confalonieri, R., Guidotti, R., Del Ser, J., Díaz-Rodríguez, N., and Herrera, F. (2023). Explainable artificial intelligence (xai): What we know and what is left to attain trustworthy artificial intelligence. *Information Fusion*, 99:101805.

Appleton, J. (1975). *The Experience of Landscape*. John Wiley & Sons, London.

Asim, F., Chani, P., Shree, V., and Rai, S. (2023). Restoring the mind: A neuropsychological investigation of university campus built environment aspects for student well-being. *Building and Environment*, 244:110810.

Azegami, K., Kawakubo, S., Sugiyama, M., and Arata, S. (2023). Effects of solar radiation in the streets on pedestrian route choice in a city during the summer season. *Building and Environment*, 235:110250.

Bai, Y. and Jin, H. (2023). Effects of visual, thermal, and acoustic comfort on the psychological restoration of the older people in a severe cold city. *Building and Environment*, 239:110402.

Berman, M. G., Hout, M. C., Kardan, O., Hunter, M. R., Yourganov, G., Henderson, J. M., and Jonides, J. (2014). The perception of naturalness correlates with low-level visual features of environmental scenes. *Journal of Environmental Psychology*, 38:38–46.

Berman, M. G., Jonides, J., and Kaplan, S. (2008). The cognitive benefits of interacting with nature. *Psychological Science*, 19(12):1207–1212.

Berry, R., Livesley, S. J., and Aye, L. (2013). Tree canopy shade impacts on solar irradiance received by building walls and their surface temperature. *Build. Environ.*, 69:91–100.

Biljecki, F. and Ito, K. (2021). Street view imagery in urban analytics and gis: A review. *Landscape and Urban Planning*, 215:104217.

Bornioli, A. and Subiza-Pérez, M. (2023). Restorative urban environments for healthy cities: a theoretical model for the study of restorative experiences in urban built settings. *Landscape Research*, 48(1):152–163.

Brown, D. K., Barton, J. L., and Gladwell, V. F. (2013a). Viewing Nature Scenes Positively Affects Recovery of Autonomic Function Following Acute-Mental Stress. *Environmental Science & Technology*, 47(11):5562–5569.

Brown, D. K., Barton, J. L., and Gladwell, V. F. (2013b). Viewing nature scenes positively affects recovery of autonomic function following acute mental stress. *Environmental Science & Technology*, 47(11):5562–5569.

Bröde, P., Krüger, E. L., Rossi, F. A., and Fiala, D. (2012). Predicting urban outdoor thermal comfort by the universal thermal climate index UTCI–a case study in southern brazil. *Int. J. Biometeorol.*, 56(3):471–480.

Cambaco, O., Landtwing, J., Cossa, H., Macete, E., Utzinger, J., Torres, N., and Winkler, M. S. (2024). Adolescent health and well-being in the context of impact assessment of natural resource extraction projects: A scoping review. *Environmental Impact Assessment Review*, 105:107360.

Celikors, E. and Wells, N. M. (2022). Are low-level visual features of scenes associated with perceived restorative qualities? *Journal of Environmental Psychology*, 81:101800.

Chen, D., Yin, J., Yu, C.-P., Sun, S., Gabel, C., and Spengler, J. D. (2024). Physiological and psychological responses to transitions between urban built and natural environments using the cave automated virtual environment. *Landscape and Urban Planning*, 241:104919.

Chen, K., Xu, Q., Leow, B., and Ghahramani, A. (2023). Personal thermal comfort models based on physiological measurements – A design of experiments based review. *Building and Environment*, 228:109919.

Chen, W., Wu, A. N., and Biljecki, F. (2021). Classification of urban morphology with deep learning: Application on urban vitality. *Computers, Environment and Urban Systems*, 90:101706.

Cheng, B., Misra, I., Schwing, A. G., Kirillov, A., and Girdhar, R. (2022). Masked-attention mask transformer for universal image segmentation. In *Proceedings of the IEEE/CVF conference on computer vision and pattern recognition*, pages 1290–1299.

Cheng, S., Jiang, P., Biljecki, F., and van Ameijde, J. (2025). The restorative value of urban environments: A systematic review of existing methods and data. Manuscript under review.

Chrisinger, B. and King, A. (2018). Stress experiences in neighborhood and social environments (sense): a pilot study to integrate the quantified self with citizen science to improve the built environment and health. *International Journal of Health Geographics*, 17:17.

Ding, Y., Lee, C., Chen, X., Song, Y., Newman, G., Lee, R., Lee, S., Li, D., and Sohn, W. (2024). Exploring the association between campus environment of higher education and student health: A systematic review of findings and measures. *Urban Forestry & Urban Greening*, 91:128168.

Dong, H. and Qin, B. (2017). Exploring the link between neighborhood environment and mental wellbeing: A case study in Beijing, China. *Landscape and Urban Planning*, 164:71–80.

Ewing, R. and Handy, S. (2009). Measuring the unmeasurable: Urban design qualities related to walkability. *Journal of Urban Design*, 14(1):65–84.

Fujiwara, K., Khomiakov, M., Yap, W., Ignatius, M., and Biljecki, F. (2024a). Microclimate vision: Multimodal prediction of climatic parameters using street-level and satellite imagery. *Sustainable Cities and Society*, 114:105733.

Fujiwara, K., Khomiakov, M., Yap, W., Ignatius, M., and Biljecki, F. (2024b). A panorama-based technique to estimate sky view factor and solar irradiance using semantic segmentation and binarization. *Building and Environment*, 266:112071.

Gong, F.-Y., Zeng, Z.-C., Zhang, F., Li, X., Ng, E., and Norford, L. K. (2018). Mapping sky, tree, and building view factors of street canyons in a high-density urban environment. *Building and Environment*, 134:155–167.

Guo, S., Zhou, Y., Yu, J., and Yang, L. (2022). Effects of the Combination of Audio and Visual Factors on Mental Restoration in a Large-Scale Urban Greenway: Perspectives from Wuhan, China. *Land*, 11(11):2017.

Hartig, T., Korpela, K., Evans, G. W., and Gärling, T. (1997). A measure of restorative quality in environments. *Scandinavian Housing and Planning Research*, 14(4):175–194.

Hartig, T. and Staats, H. (2006). The need for psychological restoration as a determinant of environmental preferences. *Journal of Environmental Psychology*, 26(3):215–226.

Helbich, M., Yao, Y., Liu, Y., Zhang, J., Liu, P., and Wang, R. (2019). Using deep learning to examine street view green and blue spaces and their associations with geriatric depression in beijing, china. *Environment international*, 126:107–117.

Herzog, T. R. and Kaplan, R. (1998). *Environmental Psychology: An Interdisciplinary Perspective*, chapter The psychological benefits of scenic beauty: Viewing preference, restoration, and the natural environment, pages 112–134. Springer.

Ito, K., Kang, Y., Zhang, Y., Zhang, F., and Biljecki, F. (2024). Understanding urban perception with visual data: A systematic review. *Cities*, 152:105169.

Ito, K., Zhu, Y., Abdelrahman, M., Liang, X., Fan, Z., Hou, Y., Zhao, T., Ma, R., Fujiwara, K., Ouyang, J., Quintana, M., and Biljecki, F. (2025). Zensvi: An open-source software for the integrated acquisition, processing and analysis of street view imagery towards scalable urban science.

Jeon, J., Jo, H., and Lee, K. (2021). Potential restorative effects of urban soundscapes: Personality traits, temperament, and perceptions of VR urban environments. *LANDSCAPE AND URBAN PLANNING*, 214.

Jeon, J. Y., Jo, H. I., and Lee, K. (2023). Psycho-physiological restoration with audio-visual interactions through virtual reality simulations of soundscape and landscape experiences in urban, waterfront, and green environments. *Sustainable Cities and Society*, 99:104929.

Ji, Q., Yin, M., Li, Y., and Zhou, X. (2023). Exploring the influence path of high-rise residential environment on the mental health of the elderly. *Sustainable Cities and Society*, 98:104808. 20 citations (Semantic Scholar/DOI) [2025-03-16].

Jiang, C., Hu, Y., Huang, T., Guo, Y., Yuan, Z., and Yuan, Q. (2025). Walk or not? Effectiveness of walking on the immune level in residential outdoor space in severely cold regions. *Building and Environment*, 270:112486.

Jiang, Y., Li, N., Yongga, A., and Yan, W. (2022). Short-term effects of natural view and daylight from windows on thermal perception, health, and energy-saving potential. *BUILDING AND ENVIRONMENT*, 208.

Kajosaari, A. and Pasanen, T. P. (2021). Restorative benefits of everyday green exercise: A spatial approach. *Landscape and Urban Planning*, 206:103978.

Kang, J. (2006). *Urban Sound Environment*. CRC Press, London.

Kaplan, R. and Kaplan, S. (1989). The experience of nature: A psychological perspective. *Cambridge University Press*.

Kaplan, S. (1995). The restorative benefits of nature: Toward an integrative framework. *Journal of Environmental Psychology*, 15(3):169–182. Green Psychology.

Kexin Sun, Li, Z., Zheng, S., and Qu, H. (2024). Quantifying environmental characteristics on psychophysiological restorative benefits of campus window views. *Building and Environment*, 262:111822.

Korpilo, S., Nyberg, E., Vierikko, K., Ojala, A., Kaseva, J., Lehtimäki, J., Kopperoinen, L., Cerwén, G., Hedblom, M., Castellazzi, E., and Raymond, C. M. (2024). Landscape and soundscape quality promote stress recovery in nearby urban nature: A multisensory field experiment. *Urban Forestry & Urban Greening*, 95:128286.

Le, Q. H., Kwon, N., Nguyen, T. H., Kim, B., and Ahn, Y. (2024). Sensing perceived urban stress using space syntactical and urban building density data: A machine learning-based approach. *Building and Environment*, 266:112054.

Lee, H. and Mayer, H. (2021). Solar elevation impact on the heat stress mitigation of pedestrians on tree-lined sidewalks of E-W street canyons – analysis under central european heat wave conditions. *Urban For. Urban Greening*, 58:126905.

Lei, B., Liu, P., Liang, X., Yan, Y., and Biljecki, F. (2025). Developing the urban comfort index: Advancing liveability analytics with a multidimensional approach and explainable artificial intelligence. *Sustainable Cities and Society*, page 106121.

Li, S., Chen, T., Chen, F., and Mi, F. (2023). How Does the Urban Forest Environment Affect the Psychological Restoration of Residents? A Natural Experiment in Environmental Perception from Beijing. *Forests*, 14(10):1986.

Lindal, P. J. and Hartig, T. (2013). Architectural variation, building height, and the restorative quality of urban residential streetscapes. *Journal of Environmental Psychology*, 33:26–36.

Liu, L., Qu, H., Ma, Y., Wang, K., and Qu, H. (2022). Restorative benefits of urban green space: Physiological, psychological restoration and eye movement analysis. *Journal of Environmental Management*, 301:113930.

Liu, P., Zhao, T., Luo, J., Lei, B., Frei, M., Miller, C., and Biljecki, F. (2023). Towards human-centric digital twins: Leveraging computer vision and graph models to predict outdoor comfort. *Sustainable Cities and Society*, 93:104480.

Liu, Q., Wang, X., Liu, J., Zhang, G., An, C., Liu, Y., Fan, X., Hu, Y., and Zhang, H. (2021). The Relationship between the Restorative Perception of the Environment and the Physiological and Psychological Effects of Different Types of Forests on University Students. *International Journal of Environmental Research and Public Health*, 18(22):12224.

Lundberg, S. M. and Lee, S. (2017). A unified approach to interpreting model predictions. *CoRR*, abs/1705.07874.

Luo, L. and Jiang, B. (2022). From oppressiveness to stress: A development of stress reduction theory in the context of contemporary high-density city. *Journal of Environmental Psychology*, 84:101883.

Ma, H., Xu, Q., and Zhang, Y. (2023). High or low? Exploring the restorative effects of visual levels on campus spaces using machine learning and street view imagery. *Urban Forestry & Urban Greening*, 88:128087.

Ma, H., Zhang, Y., Liu, P., Zhang, F., and Zhu, P. (2024). How does spatial structure affect psychological restoration? A method based on graph neural networks and street view imagery. *Landscape and Urban Planning*, 251:105171.

Ma, X., Ma, C., Wu, C., Xi, Y., Yang, R., Peng, N., Zhang, C., and Ren, F. (2021). Measuring human perceptions of streetscapes to better inform urban renewal: A perspective of scene semantic parsing. *Cities*, 110:103086.

Masullo, M., Maffei, L., Pascale, A., Senese, V. P., De Stefano, S., and Chau, C. K. (2021). Effects of Evocative Audio-Visual Installations on the Restorativeness in Urban Parks. *Sustainability*, 13(15):8328.

Middel, A., Häb, K., Brazel, A. J., Martin, C. A., and Guhathakurta, S. (2014). Impact of urban form and design on mid-afternoon microclimate in phoenix local climate zones. *Landsc. Urban Plan.*, 122:16–28.

Myin-Germeys, I. and Kuppens, P. (2021). Smartphone-based ecological momentary assessment of well-being: A systematic review and recommendations for future studies. *Journal of Happiness Studies*, 22(5):2361–2408.

Ning, W., Yin, J., Chen, Q., and Sun, X. (2023). Effects of brief exposure to campus environment on students' physiological and psychological health. *Frontiers in Public Health*, 11. Publisher: Frontiers.

Ojala, A., Korpela, K., Tyrväinen, L., Tiittanen, P., and Lanki, T. (2019). Restorative effects of urban green environments and the role of urban-nature orientedness and noise sensitivity: A field experiment. *Health & Place*, 55:59–70.

Olafsdottir, G., Cloke, P., and Vögele, C. (2017). Place, green exercise and stress: An exploration of lived experience and restorative effects. *Health & Place*, 46:358–365.

Parsons, R., Tassinary, L. G., Ulrich, R. S., Hebl, M. R., and Grossman-Alexander, M. (1998). The view from the road: Implications for stress recovery and immunization. *Journal of Environmental Psychology*, 18(2):113–140.

Payne, S. R. and Bruce, N. (2019). Exploring the Relationship between Urban Quiet Areas and Perceived Restorative Benefits. *International Journal of Environmental Research and Public Health*, 16(9):1611.

Pazhouhanfar, M. and M.S., M. K. (2014). Effect of predictors of visual preference as characteristics of urban natural landscapes in increasing perceived restorative potential. *Urban Forestry & Urban Greening*, 13(1):145–151.

Rathmann, J., Beck, C., Flutura, S., Seiderer, A., Aslan, I., and Andre, E. (2020). Towards quantifying forest recreation: Exploring outdoor thermal physiology and human well-being along exemplary pathways in a central European urban forest (Augsburg, SE-Germany). *URBAN FORESTRY & URBAN GREENING*, 49.

Roe, J., Barnes, L., Napoli, N. J., and Thibodeaux, J. (2019). The Restorative Health Benefits of a Tactical Urban Intervention: An Urban Waterfront Study. *Frontiers in Built Environment*, 5:71.

Rossetti, T., Lobel, H., Rocco, V., and Hurtubia, R. (2019). Explaining subjective perceptions of public spaces as a function of the built environment: A massive data approach. *Landscape and urban planning*, 181:169–178.

San Juan, C., Subiza-Pérez, M., and Vozmediano, L. (2017). Restoration and the City: The Role of Public Urban Squares. *Frontiers in Psychology*, 8.

Sheikh, W. T. and van Ameijde, J. (2022). Promoting livability through urban planning: A comprehensive framework based on the "theory of human needs". *Cities*, 131:103972.

Shiffman, S., Stone, A. A., and Hufford, M. R. (2008). Ecological momentary assessment. *Annual Review of Clinical Psychology*, 4:1–32.

Shin, H.-S. and Woo, A. (2024). Analyzing the effects of walkable environments on nearby commercial property values based on deep learning approaches. *Cities*, 144:104628.

Stigsdotter, U. K., Corazon, S. S., Sidenius, U., Kristiansen, J., and Grahn, P. (2017). It is not all bad for the grey city – A crossover study on physiological and psychological restoration in a forest and an urban environment. *Health & Place*, 46:145–154.

Subiza-Pérez, M., Korpela, K., and Pasanen, T. (2021). Still not that bad for the grey city: A field study on the restorative effects of built open urban places. *Cities*, 111:103081.

Tartarini, F., Frei, M., Schiavon, S., Chua, Y. X., and Miller, C. R. (2023). Cozie apple: An ios mobile and smartwatch application for environmental quality satisfaction and physiological data collection. *Journal of Physics: Conference Series*, 2600(14):142003.

Torku, A., Chan, A. P., Yung, E. H., and Seo, J. (2021). The influence of urban visuospatial configuration on older adults' stress: A wearable physiological-perceived stress sensing and data mining based-approach. *Building and Environment*, 206:108298.

Uebel, K., Marselle, M., Dean, A. J., Rhodes, J. R., and Bonn, A. (2021). Urban green space soundscapes and their perceived restorativeness. *People and Nature*, 3(3):756–769.

Ulrich, R. S. (1984). View through a window may influence recovery from surgery. *Science*, 224(4647):420–421.

Wang, L., Zhou, Y., Wang, F., Ding, L., Love, P. E. D., and Li, S. (2021). The Influence of the Built Environment on People's Mental Health: An Empirical Classification of Causal Factors. *Sustainable Cities and Society*, 74:103185.

Watson, D., Clark, L. A., and Tellegen, A. (1988). Development and validation of brief measures of positive and negative affect: The panas scales. *Journal of Personality and Social Psychology*, 54(6):1063–1070.

Weber, A. M. and Trojan, J. (2018). The Restorative Value of the Urban Environment: A Systematic Review of the Existing Literature. *Environmental Health Insights*, 12:1178630218812805.

Wilkie, S. and Clouston, S. (2019). Nature as a simple and effective mood booster: A randomized controlled trial. *Applied Psychology: Health and Well-Being*, 11(3):404–421.

Wu, Y., Liu, Q., Hang, T., Yang, Y., Wang, Y., and Cao, L. (2024). Integrating restorative perception into urban street planning: A framework using street view images, deep learning, and space syntax. *Cities*, 147:104791.

Xi, T., Li, Q., Mochida, A., and Meng, Q. (2012). Study on the outdoor thermal environment and thermal comfort around campus clusters in subtropical urban areas. *BUILDING AND ENVIRONMENT*, 52:162–170.

Xiang, L., Cai, M., Ren, C., and Ng, E. (2021). Modeling pedestrian emotion in high-density cities using visual exposure and machine learning: Tracking real-time physiology and psychology in Hong Kong. *Building and Environment*, 205:108273.

Xie, Y., Wang, X., Wen, J., Geng, Y., Yan, L., Liu, S., Zhang, D., and Lin, B. (2022). Experimental study and theoretical discussion of dynamic outdoor thermal comfort in walking spaces: Effect of short-term thermal history. *Building and Environment*, 216:109039. 49 citations (Semantic Scholar/DOI) [2025-05-13].

Xu, J., Xu, X., Wang, Z., Chen, H., Ren, Q., Huang, H., Cui, Y., An, R., and Liu, Y. (2024a). Investigating thermal exposure during daily walking through a human-scale approach: An analysis of a hot summer in Wuhan. *Building and Environment*, 264:111932.

Xu, W., Wang, H., Su, H., Sullivan, W. C., Lin, G., Pryor, M., and Jiang, B. (2024b). Impacts of sights and sounds on anxiety relief in the high-density city. *Landscape and Urban Planning*, 241:104927.

Yang, L., Kang, B., Huang, Z., Zhao, Z., Xu, X., Feng, J., and Zhao, H. (2024). Depth anything v2. *arXiv preprint arXiv:2406.09414*.

Yuan, J., Farnham, C., and Emura, K. (2021). Effect of different reflection directional characteristics of building facades on outdoor thermal environment and indoor heat loads by CFD analysis. *Urban Climate*, 38:100875.

Zhang, F., Salazar-Miranda, A., Duarte, F., Vale, L., Hack, G., Chen, M., Liu, Y., Batty, M., and Ratti, C. (2024a). Urban visual intelligence: Studying cities with artificial intelligence and street-level imagery. *Annals of the American Association of Geographers*, 114(5):876–897.

Zhang, F., Zhou, B., Liu, L., Liu, Y., Fung, H. H., Lin, H., and Ratti, C. (2018). Measuring human perceptions of a large-scale urban region using machine learning. *Landscape and Urban Planning*, 180:148–160.

Zhang, J., Liu, S., Liu, K., and Bian, F. (2025). How does campus-scape influence university students' restorative experiences: Evidences from simultaneously collected physiological and psychological data. *Urban Forestry & Urban Greening*, 107:128779.

Zhang, X., Lin, E. S., Tan, P. Y., Qi, J., Ho, R., Sia, A., Waykool, R., Song, X. P., Olszewska-Guizzo, A., Meng, L., and Cao, Y. (2024b). Beyond just green: Explaining and predicting restorative potential of urban landscapes using panorama-based metrics. *Landscape and Urban Planning*, 247:105044.

Zhang, X., Qi, J., Lin, E. S., Tan, P. Y., Ho, R., Sia, A., Song, X. P., Waykool, R., and Olszewska-Guizzo, A. (2024c). Towards healthy cities: Modeling restorative potential of urban environments by coupling LiDAR-derived 3D metrics with panorama-based online survey. *Environmental Impact Assessment Review*, 106:107497.

Zhao, T., Liang, X., Tu, W., Huang, Z., and Biljecki, F. (2023). Sensing urban soundscapes from street view imagery. *Computers, Environment and Urban Systems*, 99:101915.

Zheng, C. (2018). Assessing the Impact of High-density High-heterogeneity Urban District Landscape on Psychological Health and Optimizing via Evidence-based Design. *Landscape Architecture*, 25(1):106–111. Publisher: Beijing Landscape architecture Journal Periodical Office Co., Ltd.

Zhou, C., Zhang, S., Zhao, M., Wang, L., Chen, J., and Liu, B. (2023). Investigating the dynamicity of sentiment predictors in urban green spaces: A machine learning-based approach. *Urban Forestry & Urban Greening*, 89:128130.