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Exploring the Links Amongst Place Attachment, Urban Environment Qualities, and Psychological Restoration: A Case Study of Hong Kong

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Abstract

Urbanisation often exacerbates psychological stress, partly due to a lack of psychological connection to urban spaces. While place attachment — the multidimensional bond between individuals and their surroundings — is known to benefit well-being, its specific influence on restorative perceptions at city or regional scale remains underexplored. This study introduces an innovative framework to investigate how place attachment levels affect restoration perception by analysing links between visual features, restorative qualities, and outcomes. Using street-level imagery, a survey (n=547) was conducted in Hong Kong to gather restorative perceptions from residents with varied attachment levels. Machine learning models were then trained on this data and 25,194 street view images to map attachment variations at a regional scale. The research identifies key differences in restorative perceptions between populations with different place attachment levels, analysing survey-based variations, feature importance in machine learning, spatial disparities, and pathway relationships. The findings highlight the significant role of place attachment in contributing to restorative experiences, with high place attachment individuals showing stronger psychological recovery in urban environments. Moreover, spatial differences between high- and low-PA groups are greater in suburban areas. While high-attachment residents derive restoration from greenery, symbolic features, and high design qualities, low-attachment groups derive restoration from structural elements (e.g., roads and walls) that provide clear scope and spatial legibility. These insights offer perspectives on planning principles that foster a deeper connection to place. They propose tiered strategies tailored to the distinct needs of new developments versus historical districts, potentially supporting citizens' long-term psychological well-being.

Keywords: human perception, urban restorative value, place attachment, street view imagery, machine learning, Structural Equation Modelling (SEM)

1. Introduction

High-density urban planning, while offering sustainability benefits, may contribute to higher rates of anxiety, mood disorders, and psychosis amongst city dwellers (Luo and Jiang, 2022; Lei et al., 2025). Stressors in residents' daily lives, such as traffic congestion, environmental pollution, and constrained access to open spaces, significantly harm mental well-being (Dong and Qin, 2017). These issues point to the importance of considering psychological health in urban planning, with growing attention towards urban restoration — how urban environments facilitate emotional recovery and relaxation (Hartig et al., 1997). In this context, assessing the restorative potential of urban spaces constitutes a crucial step towards mitigating urban mental health challenges (Hipp et al., 2016; Schertz et al., 2025).

Restorative perception research has long focused on natural environments, such as parks, while largely overlooking the restorative potential of urban built environments (Kaplan, 1995; Weber and Trojan, 2018). Given the unequal access to natural spaces for many urban residents (Kaplan and Kaplan, 1989), it is critical to identify restorative opportunities within everyday urban settings. Recent studies highlight that well-designed urban spaces, and high-quality streetscapes can also offer restorative benefits (Lindal and Hartig, 2013; Lomas et al., 2021), suggesting that everyday built environments may partially compensate for unequal access to nature (Cheng et al., 2027).

Streets play a crucial role in shaping urban well-being, not only as transportation corridors but also as spaces for social interaction and psychological restoration (Ito et al., 2024; Kang et al., 2023; Le et al., 2024). Their restorative potential is shaped by design features that influence spatial coherence, visual comfort, and environmental quality (Chang et al., 2022; Ma et al., 2024). While well-integrated greenery and pedestrian-oriented amenities enhance restorative experiences, factors such as excessive built density and visual complexity can detract from them (Subiza-Pérez et al., 2021; San Juan et al., 2017; Ma et al., 2024; Zhang et al., 2024b). In addition, sensory aspects such as lighting and openness further contribute positively to psychological recovery (Celikors and Wells, 2022; Ma et al., 2023). Understanding these design influences is critical for leveraging streets as restora-

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tive urban spaces, and for informing the design of environments that support pedestrians' well-being (Lindal and Hartig, 2013; Wu et al., 2024).

Notably, urban restorative perceptions are not solely shaped by the physical features of buildings and streets but are also deeply influenced by the social and emotional connections individuals form with specific places. This connection, known as Place Attachment (PA), is a multidimensional construct comprising not only emotional bonds but also cognitive and functional ties to an environment (Scannell and Gifford, 2010; Jorgensen and Stedman, 2001). It involves place identity (the cognitive link between a place and one's self-concept), place dependence (the functional ability of a place to meet one's needs), and place bonding (the affective or emotional ties) (Kyle et al., 2004). When supported by these multidimensional connections, the restorative potential of urban spaces is enhanced (Subiza-Pérez et al., 2020; Ratcliffe and Korpela, 2016). The more a place is embedded in a person's life, memories, and self-concept, the stronger the psychological bond, which in turn enhances the restoration and aesthetic enjoyment in these environments (Ratcliffe and Korpela, 2016; Subiza-Pérez et al., 2020). However, urbanisation and gentrification pose threats to these bonds, disrupting PA and, in turn, diminishing long-term social and psychological well-being (Rollero and De Piccoli, 2010). In contrast, stronger emotional bonds to specific neighbourhoods have been linked to greater emotional well-being, with benefits that may extend to longer-term social and psychological health (Ng et al., 2022; Li et al., 2023a). This growing recognition of PA's impact highlights the urgent need for a deeper understanding of place attachment's role in fostering happier and more restorative urban environments.

Despite the established importance of both urban design and place attachment for psychological restoration in isolation, their interaction at the city scale remains poorly understood. Prior studies largely use small-scale, single-neighbourhood surveys (Subiza-Pérez et al., 2021; Li et al., 2023b), limiting comparisons across neighbourhoods and resident groups. Moreover, PA is often treated as a direct social predictor of restoration (Subiza-Pérez et al., 2021, 2020) rather than as a factor that may condition how design features shape restorative quality and outcomes. As PA varies across mobile, economically diverse urban populations, clarifying this interaction is important for neighbourhood-specific design and planning. Such evidence is needed to ensure that restorative environments are effective for both highly attached and less attached populations.

Recently, street view imagery (SVI) has become a promising instrument for scalable and cost-effective analyses of urban environments and their restorative potential (Biljecki and Ito, 2021; Ito et al., 2024). By extracting features such as vegetation and visual coherence from SVIs, studies have shown their associations with improved restoration quality (Celikors and Wells, 2022; Ma et al., 2023).

Despite these advancements,the literature still shows four related gaps, which move from what is evaluated, to for whom, across where, and through what mechanism:

- Most SVI-based research has concentrated on restorative quality (the environmental potential) (Ma et al., 2023; Zhang et al., 2024b), with little attention paid to restorative outcomes (psychological benefits). While restorativeness is well-studied, its actual psychological benefits, including stress reduction and relaxation, remain underexplored, limiting insights into urban design's impact on well-being.

- While previous research has explored the positive influence of place attachment on higher aesthetic preferences and restorative perception (Chang et al., 2024; Subiza-Pérez et al., 2020), it remains unclear whether and how the contribution of visual factors to restorative perceptions varies across different levels of place attachment.

- Building on this, the role of place attachment in shaping restorative experiences across different spatial contexts remains insufficiently understood.

- Finally, the complex interaction between place attachment and urban design — particularly how design features influence restorative quality and outcomes through different pathways across PA groups — remains poorly examined.

To address these gaps, this study introduces an innovative framework to investigate the influence of place attachment levels on restoration perception. By analysing the links between visual features of the built environments, their restorative qualities, and restorative outcomes, this research aims to quantify place attachment's effect through four key dimensions: (1) survey-based variations in restorative perceptions, (2) feature importance differences in machine learning predictions, (3) spatial disparities in restorative perceptions across the city, and (4) variations in pathway effects.

To the best of our knowledge, our proposed framework is the first to quantify people-place bonding's impact on restorative perceptions — and therefore psychological well-being — at the city scale. It explores how place attachment influences individuals' perceptions of restorative quality and psychological benefits, focusing on quantitative, spatial, and procedural differences between high- and low-PA groups.This innovative analytical framework offers implications for urban planning and policy making that foster place attachment and psychological well-being.

2. Literature review

2.1. Urban restorative value and place attachment

2.1.1. Restorative quality and restoration

Restorative environments play a crucial role in mitigating the adverse effects of urban stressors, such as cognitive fatigue and emotional distress, on mental well-being (Dong and Qin, 2017; Weber and Trojan, 2018). These environments facilitate the recovery of a person's biological, cognitive, psychological, and social resources, key aspects in the study of environmental psychology. A key distinction is drawn between restorativeness and restoration. Restorativeness captures the perceived qualities of settings that encourage recovery—often articulated in Attention Restoration Theory (ART) as dimensions like being-away and fascination (Kaplan, 1995). Restoration, in contrast, denotes the realized benefits people experience, including reduced stress and increased relaxation (Kajosaari and Pasanen, 2021). These constructs are typically assessed through subjective instruments (e.g., the Perceived Restorativeness Scale, PRS) and outcome measures such as self-reported stress reduction and relaxation (Hartig et al., 1997; Subiza-Pérez et al., 2017). Crucially, environments judged to be high in restorativeness are more likely to yield measurable restorative outcomes, making the link between the two central to research and practice.

While previous research has primarily focused on evaluating the restorative potential of environments, this study expands the scope by further capturing the perceived psychological benefits (restorative outcomes) citywide. By integrating both restorativeness and restoration, this study aims to provide a spatially explicit understanding of how urban environments can systematically contribute to psychological well-being.

2.1.2. Urban environments and restorative effects

Empirical evidence indicates that multiple environmental attributes shape both restorative quality and outcomes. Natural elements, such as vegetation, water, and open sky, consistently elevate perceived restoration; greater green volume, in particular, is linked to higher restorative value (Herzog et al, 1997; Kaplan, 1995; Kajosaari and Pasanen, 2021; Schertz et al., 2025). Urban design characteristics such as spatial coherence and imageability also structure psychological responses (Subiza-Pérez et al., 2021; San Juan et al., 2017). Streetscapes can either support or hinder restoration: sky exposure and road presence tend to correlate positively, whereas heavy automobile presence and large expanses of ground surface relate negatively (Cheng et al., 2026; Ma et al., 2024; Wu et al., 2024). Greater visual depth has also been associated with lower restorative perceptions (Zhang et al., 2024c).In addition, low-level visual properties, including brightness, hue, saturation, edge density, and texture, are processed early in vision and influence environmental comfort and appraisal. Lighting (often operationalized as brightness) shapes contrast and visibility: diffuse daylight is generally linked to higher restorative potential, while harsh artificial light or excessive luminance can undermine perceived comfort and recovery (Celikors and Wells, 2022; Ma et al., 2023, 2024). Overall, streets that integrate greenery, considered architectural form, and accessible public amenities tend to improve pedestrian experience and support positive psychological outcomes, thereby increasing restorative value (Lindal and Hartig, 2013; Wu et al., 2024).

2.1.3. Place attachment and restorative effects

Place attachment is widely recognised as a fundamental human process that links individuals to their environments, contributing significantly to psychological well-being (Scannell and Gifford, 2010). While early definitions often focused primarily on emotional bonds, contemporary literature conceptualises place attachment as a multidimensional construct (Jorgensen and Stedman, 2001; Kyle et al., 2004). This multidimensionality typically encompasses three key components: place identity, place dependence, and place bonding (or affect). Place identity refers to the cognitive connection where a place becomes a part of an individual's self-concept and personal history (Proshansky, 1978). Place dependence represents the functional attachment, reflecting the degree to which a setting facilitates an individual's goals and activities better than alternative settings (Stokols and Shumaker, 1981). Finally, place bonding captures the affective and emotional ties that provide a sense of security and belonging (Bowlby, 1969; Scannell and Gifford, 2010).

Theoretical models suggest that all three dimensions contribute to restorative experiences. From a cognitive perspective (place identity), familiar places that affirm one's identity require less cognitive effort to process, thereby facilitating the recovery of directed attention as described in Attention Restoration Theory (Kaplan, 1995). Functionally (place dependence), environments that support one's daily needs reduce frustration and stress, contributing to a more restorative experience (Kyle et al., 2004). Emotionally (place bonding), the affect-regulation model suggests that meaningful places evoke positive emotions that directly counteract stress (Schore, 2001; Korpela and Ylén, 2009). Consequently, measuring place attachment fully — by combining identity, dependence, and bonding — is necessary to see its real effect on how restorative a city can be.

Empirical evidence supports these theoretical connections. Chang et al. (2024) found that in natural environments, features that strengthened place attachment also enhanced perceived restoration. Similarly, Korpela and Hartig (1996) and Korpela and Ylén (2009) demonstrated that ”favourite places”, which are typically characterised by high levels of identity and dependence, are used by individuals specifically for emotional regulation and self-restoration. Ratcliffe and Korpela (2016) and Ratcliffe and Korpela (2016) further found that places embedded with personal memories (identity) generate stronger aesthetic and restorative responses. Evidence from the Global South also suggests that place attachment can remain strong in environments shaped by informality, socio-spatial inequality, and urban precarity. For example, studies in Harare show that residents in informal neighbourhoods may develop durable place bonds despite material constraints, and that these bonds are shaped by both individual and neighbourhood conditions (Bandauko et al., 2022, 2024). This perspective is important because it suggests that place attachment should not be understood simply as a by-product of physical environmental quality; rather, it is a socially embedded relationship that may alter how urban environments are perceived and valued. While Raymond et al. (2010) provided a robust framework for measuring these dimensions, the specific pathways between these combined attachment dimensions and restorative outcomes in dense urban settings require further exploration.

Importantly, place attachment may also shape how urban environments are perceived and appraised (Scannell and Gifford, 2010; Jorgensen and Stedman, 2001; Rollero and De Piccoli, 2010). Because attached places are more likely to carry personal meaning, familiarity, and functional relevance, individuals may not respond to streetscapes solely on the basis of their observable physical attributes (Stedman, 2003; Ratcliffe and Korpela, 2016). Instead, visual environments may be interpreted through prior experience, everyday use, and symbolic associations with place (Korpela and Hartig, 1996; Subiza-Pérez et al., 2020; Li et al., 2023b). In this sense, place attachment can be understood not only as a correlate of restoration, but also as a potential moderator of the relationship between streetscape characteristics and restorative perception.

However, the relationship between place attachment and restoration in urban environments remains inconsistent. For instance, Subiza-Pérez et al. (2021) reported insignificant associations between place attachment and restoration in certain urban plazas, suggesting that the restorative benefit of attachment may depend on specific environmental contexts. These mixed findings highlight the need for a more systematic investigation. Specifically, important gaps persist: While place attachment is often treated as a single variable, fewer studies have looked at how groups with different levels of attachment react differently to the restorative qualities of physical features. Furthermore, spatial heterogeneity is under-examined; the interplay between place identity, dependence, and visual streetscape features likely varies across different neighbourhoods. Understanding these differences is essential for inclusive urban planning that addresses the needs of diverse populations.

2.2. *Streetscape application on study design quality and perception*

Given that restorative experiences are shaped not only by environmental attributes themselves but also by how those attributes are perceived, street view imagery (SVI), with its wide coverage, fine spatial resolution, and pedestrian perspective, has become an essential tool for assessing urban visual quality (Biljecki and Ito, 2021). Leveraging computer vision techniques such as object detection, semantic segmentation, and image classification, SVI enables both objective and subjective evaluations of streetscapes, providing insights into urban design and perception across scales.

2.2.1. *Objective design quality*

SVI-based methods have been proven effective in quantifying the physical attributes of streetscapes. Key urban elements — such as greenery, water, and sky — are quantified using pixel-based metrics (Biljecki et al., 2023). Vegetation coverage and sky openness are estimated through pixel ratios, providing insights into spatial composition and natural presence, while water features enhance aesthetic and restorative qualities (Gong et al., 2018; Helbich et al., 2019). To capture the overall visual quality of street environments, inspired by conventional urban design theory, composite mathematical formulas have been developed by recombining extracted elements such as greenery and sidewalks to proxy the concepts of the perceptions. In particular, researchers have successfully assessed design qualities, including openness, enclosure, imageability, and complexity (Ewing and Handy, 2009), by employing an automatic operational framework and visual features extracted by semantic segmentation algorithms. The framework has been validated with subjective measures (Ma et al., 2021; Song et al., 2024a), it offers pipelines to evaluate design qualities at the regional scale (Tang and Long, 2019).

2.2.2. *Subjective perception and prediction*

Beyond physical attributes, SVI has been instrumental for studying subjective perceptions of urban environments, such as safety, aesthetics, liveliness, and restorative potential, by combining computer vision–derived attributes with ML trained on human ratings (Liang et al., 2024; Ma et al., 2024). Crowdsourced datasets such as Place Pulse 2.0 aggregate perceptions of safety, beauty, and disorder, enabling large-scale prediction from SVI (Dubey et al., 2016). Trained on these data, ML models have mapped citywide streetscape perceptions across contexts (Zhang et al., 2018; Liang et al., 2023; Zhao et al., 2023; Song et al., 2024b), while the integration of deep learning with image surveys has expanded the scalability and generalizability of perception-based urban research beyond traditional, small-sample surveys (Zhang et al., 2024a).

SVI-based analysis is particularly valuable for evaluating differences in perceptions across various population groups. By incorporating socio-demographic data, studies have explored how factors such as gender and age influence perceptions of safety, beauty, wealth, and disorder (Cui et al., 2023; Kang et al., 2023). In restorative studies, SVI has been widely used to assess how environmental features — such as greenery, spatial coherence, and natural elements — contribute to restorative quality, offering insights into the psychological benefits provided by urban environments (Zhang et al., 2024b; Ma et al., 2024).

Nevertheless, most research in this area has focused on assessing 'restorative potential', which evaluates the perceived capacity of streetscapes to support restorative experiences using tools like the Perceived Restorativeness Scale (PRS) (Celikors and Wells, 2022; Ma et al., 2023). To the best of our knowledge, no studies utilizing SVI have specifically examined restorative outcomes, such as the actual psychological benefits of relaxation, stress reduction, and emotional recovery. This gap limits our understanding of how urban environments contribute to individuals' well-being in a more concrete, measurable way.

Furthermore, while several socio-demographic factors have been incorporated into restorative studies using SVI and machine learning prediction, place attachment has often been overlooked as a crucial social characteristic. This omission matters because place attachment may shape how people interpret the same streetscape features: for some individuals, visual elements such as greenery, landmarks, or familiar urban forms may carry emotional and symbolic meanings, whereas for others, more immediate cues such as openness, enclosure, or visual order may be more influential. Place attachment is known to interact with physical environments and shape restorative experiences, yet it has not been systematically integrated into the analysis. To address this gap, this study conducted an online survey that not only captured participants' restorative perceptions but also assessed their attachment levels to specific neighbourhoods. By exploring the interactive effects of place attachment and physical environmental characteristics, this study aims to uncover how emotional connectedness can condition the impact of design features on psychological restoration. In doing so, the study extends SVI-based restorative research from identifying what kinds of environments appear restorative to examining for whom, and under what attachment conditions, they are perceived as restorative.

3. Data and Methods

In this study, we introduce a comprehensive and comparative novel methodology for quantifying restorative perception of cityscape utilizing SVI, and we investigate the differences between groups of different place attachment levels. The study focuses on Hong Kong, a high-density metropolitan region where a lack of public open space exacerbates mental health challenges associated with high-pressured urban lifestyles (Tieben, 2016). The research framework is structured into three main steps (Figure 1):

Dataset construction (Section 3.1): A set of sample SVIs were selected for an online survey, where participants rated their place attachment to two districts and evaluated restorative qualities and outcomes for various SVIs. Ultimately, valid responses were collected from 547 respondents. The SVIs, obtained from Google Street View, were labelled based on average restorative scores and categorized into three classes for each of the high- and low-place attachment groups. Further, visual features were extracted from the imagery.

Model training and prediction (Section 3.2): To scale up the assessment of restorative effects beyond the selected survey locations, this study employed machine learning models to predict restorative perceptions citywide. Previous research has primarily relied on localized questionnaire surveys or single-image assessments (Lindal and Hartig, 2013), which fail to capture the broader geographic context influencing restorative experiences. To address this limitation, computer vision models were used to extract semantic segmentation, low-level features, scene depth, and place scenes. To effectively predict restorative scores using features extracted from SVIs, XGBoost was used for classification. Model performance was evaluated using macro-accuracy and F1 scores, with comparisons against baseline models. The optimal models were further selected for citywide prediction of restorative perceptions.

Perceptual differences evaluation (Section 3.3): Differences between the high- and low-PA groups were analysed from four perspectives: (1) Analyses of variance (ANOVA) to test for statistical differences in restorative scores, (2) feature importance analysis to compare the contributions of visual features, (3) aggregating predicted scores at the TPU level to map spatial distribution patterns, and (4) path and mediator effects analysed using generalized structural equation modelling (GSEM). Separate models were constructed for the high- and low-PA groups to evaluate how place attachment influences restorative perceptions.

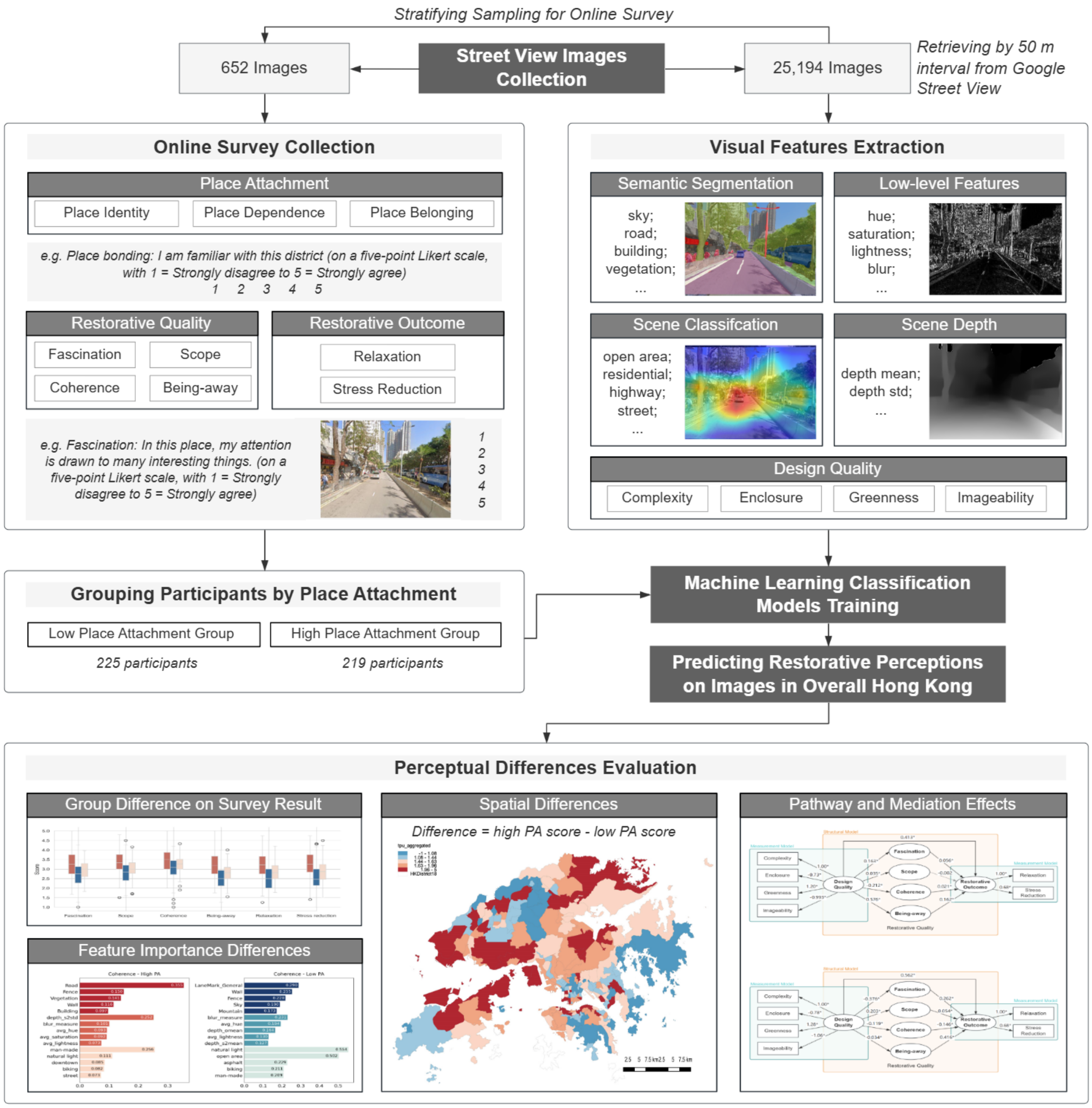

Figure 1: The framework to measure restorative perception cityscapes and the differences between groups with different attachment level to neighbourhoods. Source of imagery: Google Street View.

3.1. Dataset construction

3.1.1. Case study

Hong Kong, a Special Administrative Region in southern China, was selected for its high-density urban form where streets are central to daily life (Tieben, 2016). With limited public open space and 7.4 million residents, streets serve as transport corridors and social venues (Siu and Huang, 2015). High public transport use and associated walking

(Cheng and van Ameijde, 2023) underscore the need to understand streetscapes' restorative qualities and mechanisms, especially amid ongoing mental health challenges among the working population (Luo and Jiang, 2022).

Beyond the historic cores of Hong Kong Island and Kowloon, a series of new towns were developed from the 1960s onward. Some evolved into self-contained towns with vibrant centres, while others remain commuting-oriented "sleeping towns" with weaker vitality (Hui and Lam, 2005), often described as "non-places" for limited design quality and social cohesion (Stedman, 2003). These variations highlight the need to examine how place attachment shapes restorative potential across diverse contexts.

This study compared neighbourhood environments across the urban core and both older and newer new towns. To capture neighbourhood dynamics and assess design's role in emotional well-being, variables were aggregated at the Tertiary Planning Unit (TPU) level, enabling granular analysis of how urban environments contribute to restorative experiences and related outcomes.

3.1.2. Street view imagery

We sampled points every 50 meters along the OpenStreetMap road network and used these coordinates to acquire Google Street View (GSV) images. Following common practices (Biljecki et al., 2023), the view angle was set to align with street orientations, ensuring the optimal eye perspective of each street segment to proxy the environment. A total of 25,194 SVIs was obtained.

3.1.3. Online survey collection

To assess individuals' restorative perceptions of scenes, 652 images were selected for the survey from the obtained SVIs using a stratified sampling approach. This strategy ensured the inclusion of a wide range of environmental and geographic conditions representative of Hong Kong's heterogeneous urban settings. Specifically, we sampled SVIs (1) proportionally across the 18 administrative districts based on population distribution, and (2) across various land use types (e.g., residential, commercial, recreational) within each district to capture local visual and cultural diversity. This method follows previous studies that emphasize stratified sampling for urban image analyses (Song et al., 2024a; Liang et al., 2024; Wu et al., 2024). These images were then presented to participants, who evaluated them using a five-point Likert scale, which has been used in previous studies (Zhang et al., 2024b,c; Wu et al., 2024). To maintain consistent image quality, we inspected the images manually for common quality issues and inconsistencies such as poor weather conditions or low contrast (Hou and Biljecki, 2022), and removed those of inadequate quality.

An online survey (Table 1) was conducted through a dedicated webpage. The survey included three sections: place attachment level, restorative perceptions, and personal characteristics. To assess place attachment at the neighbourhood scale, each participant was randomly assigned two districts and asked to rate their emotional bond to each location using a five-point Likert scale. Place attachment was measured across three commonly used dimensions—place identity, place dependence, and place bonding—adapted from the work by Rollero and De Piccoli (2010).

Participants then evaluated a set of street view images associated with each assigned district. For each image, they rated their agreement on six restorative attributes using five-point Likert scales. The restorative quality questionnaire covered four main dimensions — Fascination, Scope, Coherence, and Being-away — following the work of Hartig et al. (1997) and Celikors and Wells (2022). Restorative outcomes, representing the benefits participants perceived, were measured by two questions focusing on relaxation and stress reduction (Kajosaari and Pasanen, 2021). This design linked district-level place attachment with image-level restorative ratings through a shared spatial context: respondents first reported their attachment to a district and then evaluated street scenes sampled from that same district. We therefore treated place attachment as a contextual neighbourhood-level characteristic that may shape the appraisal of specific street environments embedded within that broader setting, rather than as a response to each isolated image. This approach is consistent with the place attachment literature, which commonly conceptualises attachment in relation to meaningful place units such as neighbourhoods, communities, or activity settings rather than decontextualised visual scenes (Scannell and Gifford, 2010; Jorgensen and Stedman, 2001; Kyle et al., 2004; Rollero and De Piccoli, 2010; Raymond et al., 2010).

SVIs from the assigned districts were randomly presented, and each participant was asked to rate fourteen randomly chosen sample images for each perception dimension. To ensure fairness and consistent assessments, each image was presented approximately 10 times on average. Participants assigned scores from 1 to 5, reflecting their perceptions of the street scenes. Also, participants provided their age and gender information (Table A.7). It is worth noting that all participants were Hong Kong residents, and their age distribution approximately matched the broader population structure. A 20 HKD (2.57 USD) coupon was provided to each respondent as a compliment for completing the survey, which approximately took 10-15 minutes on average. In total, 547 valid questionnaires were collected, yielding 42,588 individual ratings. The questionnaire data passed reliability and validity

Table 1: Items and questions of the online survey.

Item	Five-point Likert scales
Restorative quality	
Fascination	In this place, my attention is drawn to many interesting things.
Scope	This place is large enough to allow exploration in many directions.
Coherence	It is easy to see how things are organized in this place.
Being-away	To stop thinking about the things that I must get done I like to go to places like this.
Restorative outcome	
Relaxation	This place can help me to relax.
Stress reduction	This place helps me to escape stress.
Place attachment	
Place bonding	I am familiar with this district.
Place identity	I have a lot of fond memories in this district.
Place dependence	Doing my activities in this district is more important to me than doing them in any other place.

testing (Table A.8).

To investigate the influence of place attachment levels on restorative quality and outcomes, participants were categorized into two groups based on the average score derived from the six place attachment questions. To avoid perceptual ambiguity and sharpen classification contrast, we excluded the middle 20% of PA scores, assigning the bottom 40% to the low PA group and the top 40% to the high PA group. This approach follows established practices in perception modelling to improve interpretability and model performance (Zhang et al., 2018). To ensure objectivity and minimize potential endogeneity, participants were randomly assigned street view images from districts that do not include their area of residence. For each PA group, image labels were then derived from the mean restorative ratings given to images within the corresponding district context. Finally, the calculated mean scores of each image were categorized into three levels, ranging from low to high restorative perception, represented by the values 0, 1, and 2.

3.2. Model training and prediction

To establish the implicit relationship between SVIs and restorative qualities and outcomes, the labels of each perception quality were used as dependent variables for prediction, which is a categorical variable of 3 classes (0, 1, 2), representing low, medium, and high levels of perceived restorative quality and outcomes. This classification approach enhances the model's interpretation ability to differentiate between varying degrees of restorative perceptions.

Explanatory variables were extracted from SVIs using ZenSVI (Ito et al., 2025), including high-level streetscape elements (e.g., greenery, sky via semantic segmentation) and low-level visual features (e.g., hue, saturation, lightness), as well as scene label and depth.

High-level features were derived via semantic segmentation (Mask2Former pretrained on Mapillary Vistas (Cheng et al., 2022)), scene labels from a ResNet trained on Places365 (He et al., 2016; Zhou et al., 2017), depth from DepthAnything v2 (Yang et al., 2024), and low-level colour statistics from OpenCV. Variables are summarized in Table 2.

We trained six tree-based classifiers (Decision Tree, Gradient Boosting, AdaBoost, Random Forest, LightGBM, XGBoost) on 70/30 train–test splits of the labeled SVI dataset (n=652; Table A.9). To mitigate class imbalance, we applied SMOTE and class weighting where applicable. Hyper-parameters were tuned with nested 5-fold cross-validation and random search, avoiding information leakage. Performance was evaluated on held-out tests across all restorative dimensions; full metrics and ablations are reported in Appendix C.

Table 2: Summary of input features: model and algorithms.

CV Categories	Model	Dataset	Input features
Semantic segmentation	Mask2Former	Mapillary Vista	24
Scene classification	ResNet	Place365	10
Scene depth	DepthAnything v2	-	8
Low-level features	OpenCV	-	10

After selecting the top 12 performing models for the six perceptions across the two PA groups, they were applied to predict citywide perception labels using explanatory features from all SVIs.

3.3. Perceptual differences evaluation

3.3.1. Group differences on survey result

To compare the differences in restorative perceptions based on survey results across the high PA, low PA, and combined groups, ANOVA was conducted for each of the six parameters: Fascination, Scope, Coherence, Being-away, Relaxation, and Stress Reduction. Box plots were also used to visualize the distribution and variability of the scores within each group. Significant differences ($p < 0.01$) were observed across all six parameters, allowing for further analysis of group-specific differences in restorative quality and outcomes.

3.3.2. Feature importance differences

To determine which visual variables contributed most to higher levels of restorative quality and outcomes, we employed Explainable Artificial Intelligence (XAI) techniques to interpret the series of models separately. Specifically, SHAP values quantified each feature's contribution to model predictions, enabling comparison of relative importance across variables (Ali et al., 2023; Lundberg and Lee, 2017). Using TreeExplainer, we computed global SHAP values and examined contributions for Class 2 (highest restorative level) to isolate features associated with stronger restorative perceptions (details in Appendix D).

For each ML model, the top five features with the highest global SHAP values were extracted across three categories: (1) semantic segmentation; (2) place scenes; (3) scene depth and low-level features. To compare the dominant features between high PA and low PA groups, we visualized the top five features for each category using a series of bar plots. These visualizations illustrate the differences in feature importance for restorative qualities and outcomes between the two groups. The comparisons provide insights into how place attachment influences the visual characteristics associated with perceived restorative benefits.

3.3.3. Spatial differences

The restorative scores predicted by the high PA and low PA models were aggregated at the TPU (Tertiary Planning Unit) level. For each TPU, the mean value of all sampling points within or overlapping the TPU boundary was calculated. This aggregation provided a comprehensive representation of restorative qualities and outcomes for each TPU. Subsequently, to facilitate comparisons across different parameters and groups, all mean scores were scaled to a range of 0–10.

To present the geographical mismatch in restorative perceptions between the high- and low-PA groups, the absolute differential values were computed based on the standardized scores. The difference for each TPU ($\Delta\mathrm{PA}_i$) was calculated as:

$$\Delta\mathrm{PA}_i = S_{hpai} - S_{lpai} \tag{1}$$

where i refers to the TPU, S_{hpai} denotes the score from the high PA model for TPU i, and S_{lpai} represents the score from the low PA model for the same TPU.

3.3.4. Estimators difference on pathway and mediation effects

Lastly, this study compares the pathway and mediation effects between design quality (DQ), restorative quality (RQ), and restorative outcomes (RO) for high PA and low PA groups using predicted perception scores. Given that the predicted perception values are ordinal, we employed the Generalized Structural Equation Model (GSEM), which accommodates non-continuous variables and large datasets, making it suitable for our research.

Separate GSEM models were constructed for the high PA group and the low PA group. In each group-specific model, we examined the pathway from design quality to restorative quality and finally to restorative outcomes, with restorative quality acting as the mediator in the model.

Four objective design quality parameters were included, following (Song et al., 2024a): Complexity, Enclosure, Greenness, and Imageability (see Appendix B for details). Latent variables for design quality and restorative outcomes were created using Confirmatory Factor Analysis (CFA). For restorative quality, single parameters were retained due to suboptimal CFA performance, as each parameter captures distinct aspects of restorative quality. Given the ordinal nature of the predicted scores and the large sample size (N = 25,052), the Weighted Least Squares Mean and Variance adjusted (WLSMV) estimator was used to construct the GSEM. WLSMV is particularly suited for ordinal categorical data and provides robust and unbiased parameter estimates in large samples (Proitsi et al., 2011). Model performance was evaluated using several metrics: Comparative Fit Index (CFI), Tucker-Lewis Index (TLI), Root Mean Square Error of Approximation (RMSEA), and Standardized Root Mean Residual (SRMR). Direct and indirect standardized estimates of variables were calculated to assess the mediator effects of restorative quality on the DQ-RO relationship, with a focus on differences between high- and low-PA groups.

4. Results and analysis

4.1. Models evaluation

Table C.10 shows that XGBoost outperforms the other non-linear classifiers across all perceptions and PA profiles. Averaged over high- and low-PA groups, XGBoost attains 0.74 accuracy; we therefore use it for subsequent interpretation.

Detailed metrics (Table C.11) indicate strong performance across restorative qualities and outcomes: mean accuracy 74% and F1 scores 64–76%, reflecting a balanced precision–recall trade-off. Stress reduction is highest (77%), whereas fascination (Low-PA) and coherence (High-PA) are lower (68% and 69%), likely reflecting greater conceptual ambiguity and context dependence. In particular, fascination may be more difficult to predict among low-PA respondents because, in the absence of strong familiarity or identity-based anchors, judgments about what is attention-holding or interesting may be more heterogeneous. The comparatively lower accuracy of this model does not invalidate the subsequent analysis, but it suggests that the feature-importance results for low-PA fascination should be interpreted more cautiously than those for the other restorative dimensions. Despite these differences, performance is consistent enough to support downstream prediction.

Furthermore, the 12 classification models were applied to the overall Hong Kong dataset to predict citywide perception labels. Detailed predicted labels in restorative perceptions can be found in the Appendix.

4.2. Perceptual differences in high/low PA groups

4.2.1. Group differences on survey result

Subsequent analyses aimed to compare perceptual differences among the high PA, low PA, and combined groups using ANOVA (see Table 3). Significant differences ($p < 0.01$) were observed in restorative perception indicators-Fascination, Scope, Coherence, Being-away, Relaxation, and Stress reduction—across the high PA, low PA, and combined groups (Figure 2).

Table 3: ANOVA analysis for different groups across variables.

Group (mean)	**Fascination**	**Scope**	**Coherence**	**Being-away**	**Relaxation**	**Stress Reduction**
Overall	2.962	3.040	3.241	2.834	2.813	2.868
High	3.258	3.337	3.486	3.241	3.200	3.229
Low	2.644	2.710	3.062	2.424	2.374	2.443
F	44.904	51.463	27.550	87.983	81.078	68.735
p	0.0	0.0	0.0	0.0	0.0	0.0

Restorative perceptions were consistently higher in the high PA group across all six parameters, indicating a strong link between place attachment and perceived restorative quality. Specifically, the high PA group reported higher mean scores in all dimensions compared to the low PA group.

The largest differences between high- and low-PA groups were observed in the restorative outcomes, particularly Relaxation and Stress Reduction, suggesting that stronger place attachment is associated with greater emotional recovery and stress relief.

Among the restorative quality parameters, the largest difference between high- and low-PA groups was observed in Being-away, indicating that the high PA group feels a greater sense of escape and distance from everyday stressors in the evaluated environments. The parameter of Coherence, on the other hand, displayed the smallest difference between groups. This may suggest that individuals, regardless of their level of place attachment, perceive the organization and order of elements in the environment similarly, particularly regarding the perceived coherence of urban spaces.

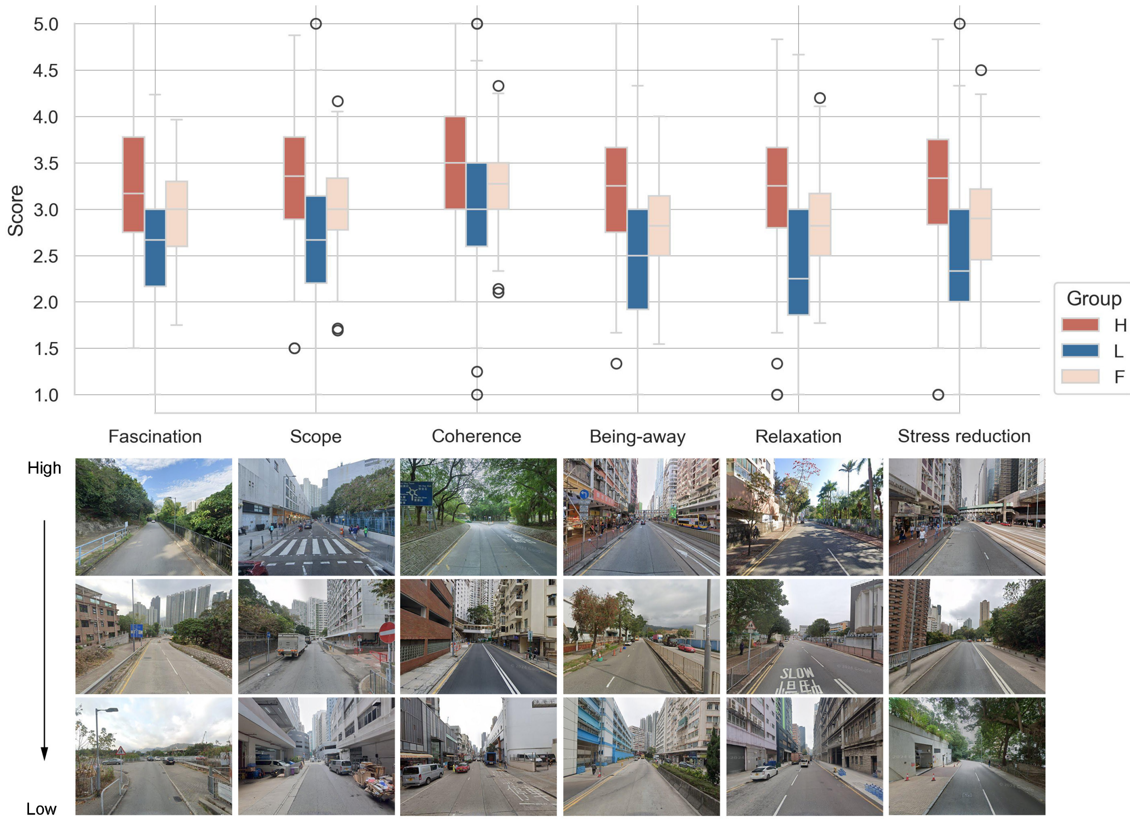

Figure 2: Box plots of perceived restorative qualities and outcomes among high PA (H), low PA (L) and overall group (F). Source of imagery: Google Street View.

4.2.2. *Feature importance differences*

Figure 3 illustrates the top five features with the highest mean SHAP values from three visual element categories for each restorative perception model. The length of each bar represents the mean SHAP value. In general, SVI visual features contribute variably to different restorative perceptions. For restorative qualities, place scenes are the most significant contributors across models, while scene depth and low-level features have moderate importance, and semantic segmentation features contribute less. In contrast, for restorative outcomes, semantic segmentation features such as *vegetation*, *walls*, and *sidewalks* become more prominent, alongside place scenes, indicating a shift in feature emphasis between the two categories. For the same restorative parameter, the most contributing features differ between high- and low-PA groups, implying a different influencing mechanism across various PA groups.

For Fascination, the semantic features with the greatest importance differ markedly

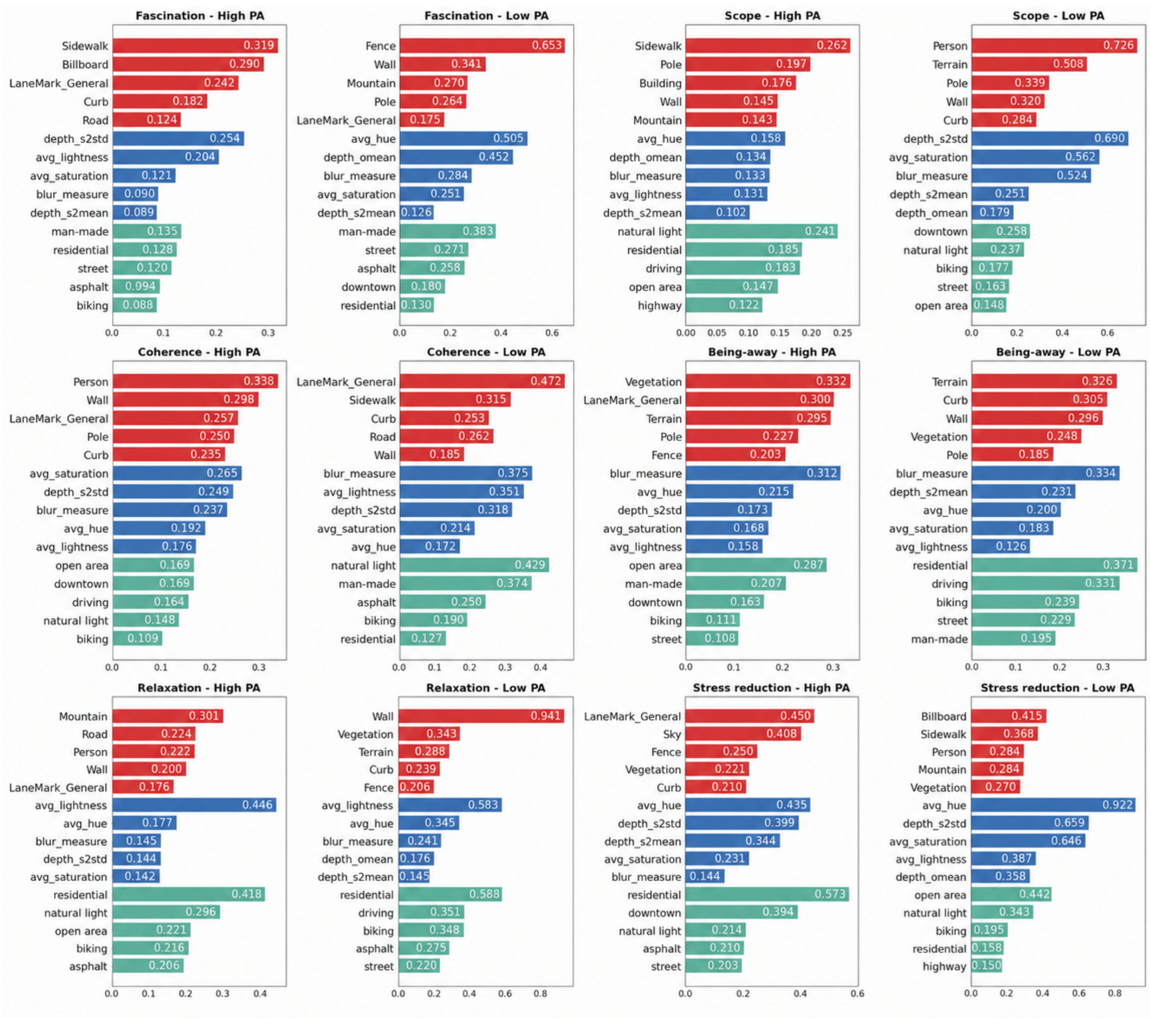

Figure 3: Feature importance differences between high PA and low PA groups. The bar plots display the feature importance for each restorative perception dimension across high PA and low PA groups. Bars are coloured by feature category, with consistent colours used across all subplots to facilitate comparison; High-PA and Low-PA models are indicated in the subplot titles.

between the two groups. The high PA model highlights street-related features such as *sidewalk*, *billboard*, and *lane markings*, while the low PA model assigns greater importance to *fence*, *wall*, *mountain*, and *pole*. The importance of scene-depth and low-level features also differs, with the high PA model emphasizing *depth standard deviation* and *average lightness*, and the low PA model highlighting *depth mean*, *average hue*, and *blur mean*. For Scope, the high PA model assigns greater importance to *sidewalk*, *pole*, and *building*, whereas the low PA model highlights *person*, *terrain*, *pole*, and *wall*. Place-scene features such as *natural light* and *open area* are more prominent in the high PA model, whereas *downtown* and *biking* receive greater importance in the low PA model.

The perception of Coherence is associated with different semantic feature profiles across groups: the high PA model assigns greater importance to *person*, *wall*, *lane markings*, and *pole*, whereas the low PA model highlights *lane markings*, *sidewalk*, *curb*, *road*, and *wall*. Scene-depth and low-level features also differ between groups, with *average saturation* and *depth standard deviation* more prominent in the high PA model, and *blur mean* and *average lightness* more prominent in the low PA model. Regarding the quality of Being-away, the high PA model assigns importance to *vegetation*, *lane markings*, and *terrain*, whereas the low PA model highlights *terrain*, *curb*, *wall*, and *vegetation*. For this parameter, low-level and scene-depth features also differ between groups, with *average hue* more prominent in the high PA model and *blur mean* and *depth mean* more prominent in the low PA model.

For restorative outcomes, the differences between PA groups follow a similar trend but with notable shifts in feature contributions. For Relaxation, the high PA model assigns greater importance to *mountain*, *road*, *person*, and *wall*, whereas the low PA model highlights *wall*, *vegetation*, *terrain*, *curb*, and *fence*. In the scene-depth and low-level categories, *average lightness* is more prominent in the high PA model, whereas *depth mean*, *depth second moment*, and *blur mean* receive greater importance in the low PA model. Finally, for Stress Reduction, the high PA model assigns importance to natural features such as *sky* and *vegetation*, whereas the low PA model highlights street-related features including *billboard*, *sidewalk*, and *person*, alongside *mountain* and *vegetation*. Low-level and scene-depth features also differ between groups, with *blur mean* more prominent in the high PA model and *average lightness* and *depth mean* more prominent in the low PA model.

Interestingly, although the specific feature profiles vary across restorative qualities and outcomes, the differences in feature importance between high- and low-PA groups reveal a recurring contrast. High-PA models more frequently assign importance to visually open or natural indicators, including *natural light* and *open area* for Scope, *vegetation* for Being-away, and *sky* and *vegetation* for Stress Reduction. Conversely, low-PA models more often highlight enclosure- and street-related features, such as *fence* and *wall* for Fascination, *wall* and *curb* for Being-away and Relaxation, and *billboard* and *sidewalk* for Stress Reduction. Scene-depth and low-level features also differ between groups, although their relative importance is more dimension-specific. Taken together, these results suggest that high- and low-PA groups rely on partly different visual cues in the modelled restorative perceptions: open and natural cues are more recurrent in high-PA models, whereas enclosed and street-oriented cues are more recurrent in low-PA models.

4.2.3. Spatial differences

This section examines how restorative perceptions vary spatially across Hong Kong, focusing on differences between high- and low-PA groups. Figure 4 visualizes the TPU-level mismatch across six restorative dimensions, while Table 4 reports their descriptive statistics. In general, individuals with high place attachment consistently report higher perceived restorative qualities and outcomes.

Table 4: Descriptive statistics for spatial mismatch at the TPU level.

	Fascination	Scope	Coherence	Being-away	Relaxation	Stress Reduction
count	211	211	211	211	211	211
mean	2.935	1.596	0.179	2.168	1.686	3.878
std	1.120	1.068	0.730	1.338	1.435	1.409
min	-0.62	-2	-1.89	1	-5	0
max	5.5	5	2.5	6.56	5	10

For restorative qualities, the degree of difference varies across dimensions. Fascination and Being-away show larger disparities between the high- and low-PA groups, with high PA groups exhibiting significantly higher values. Scope also shows a notable difference, but to a lesser extent. Coherence shows smaller differences, indicating more similar perceptions between the two groups, particularly in evaluating how elements are organized in a place. Spatial patterns in restorative perceptions vary across different regions of Hong Kong. In the densely urbanised areas of Kowloon and Hong Kong Island, minimal differences are observed between high- and low-PA groups. Among the restorative outcomes, Stress Reduction shows the largest overall mismatch across the six perceptions. Similar to restorative qualities, the urban areas of Kowloon and Hong Kong Island show smaller differences, while new towns and peripheral areas exhibit larger gaps. Interestingly, the pattern for Relaxation differs from other outcomes. The largest differences in Relaxation are observed in the metropolitan areas, particularly in Kowloon and Hong Kong Island, where high PA groups report higher relaxation levels. This could be attributed to the familiarity and social networks that individuals in these areas experience, which might provide a sense of comfort and stability that supports relaxation.

To further explore how urban context shapes these disparities, we aggregated mismatch scores at the district level. Table 5 confirmed the largest mismatch in restorative quality is observed in new town districts like Yuen Long, Tsuen Wan, and Tuen Mun, where migrant populations and urban homogeneity are more prevalent. Conversely, the largest restorative outcome mismatches are observed in dense, historically rooted areas such as

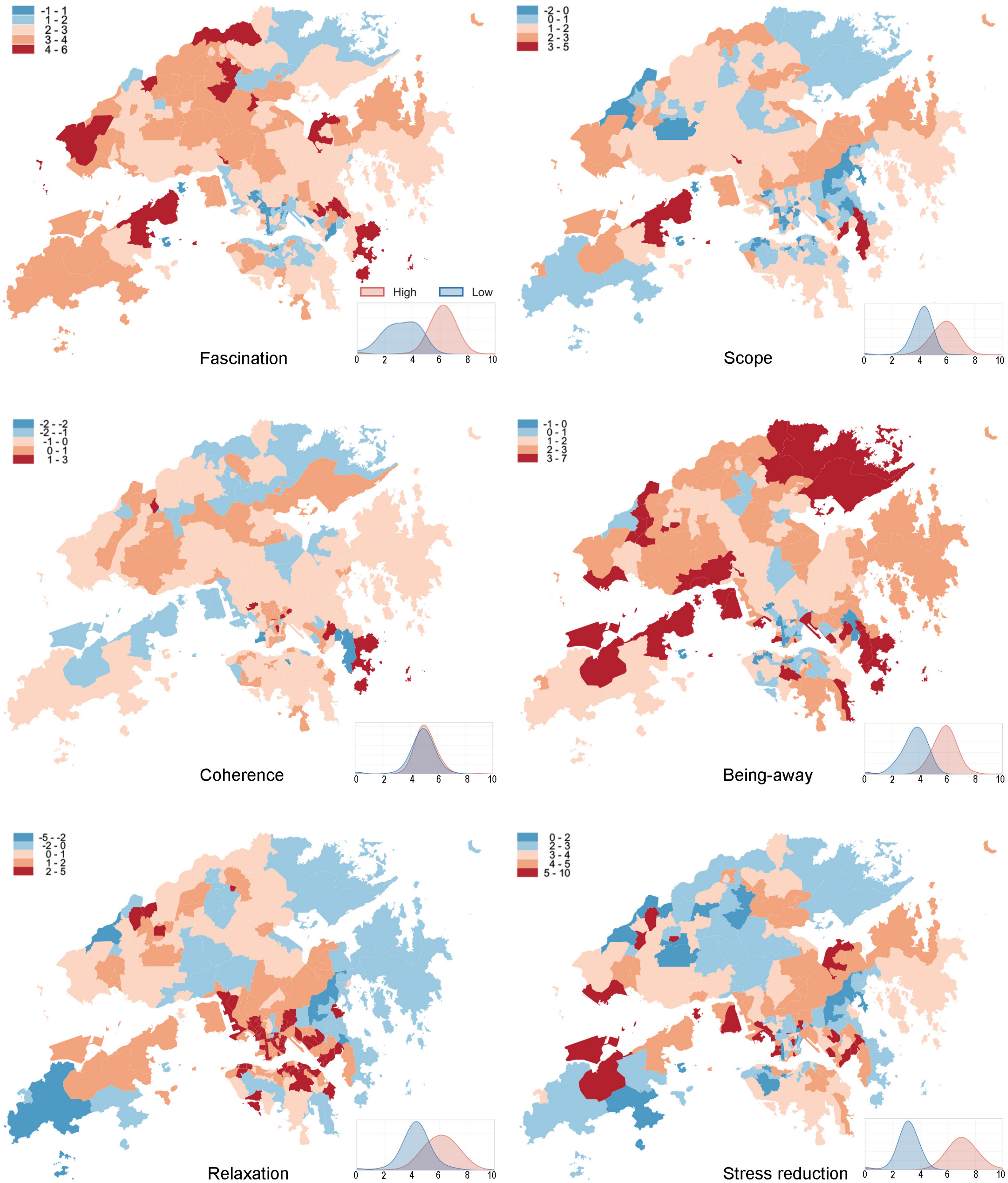

Figure 4: Spatial differences between high PA and low PA groups. The maps show the spatial difference scores at the Tertiary Planning Unit (TPU) level for six restorative dimensions. Insets show Kernel Density Estimates for high PA (red) and low PA (blue) scores.

Yau Tsim Mong, Sham Shui Po, and Kowloon City. This suggests that in suburban districts, place attachment may be more critical for fostering perceived restorative quality, whereas in metropolitan areas, it more strongly mediates psychological benefits.

Table 5: District-level mean mismatch scores for restorative quality (RQ) and restorative outcome (RO).

District	Mismatch RQ	Mismatch RO
Central and Western	1.45	2.51
Eastern	1.57	3.04
Islands	1.93	1.85
Kowloon City	1.40	3.20
Kwai Tsing	1.93	3.31
Kwun Tong	1.71	3.03
North	2.03	2.42
Sai Kung	2.05	2.39
Sha Tin	1.85	2.77
Sham Shui Po	1.50	3.39
Southern	1.82	2.54
Tai Po	2.01	2.29
Tsuen Wan	2.07	2.62
Tuen Mun	2.17	2.44
Wan Chai	1.40	2.62
Wong Tai Sin	1.60	2.76
Yau Tsim Mong	1.22	3.38
Yuen Long	2.10	2.20

4.2.4. Estimators difference on pathway and mediation effects

Table E.12 summarises the performance metrics for the GSEM models, demonstrating a robust model fit and high accuracy for both the high- and low-PA groups. Figure 5 reveals key differences in the pathways estimates between the high- and low-PA groups.

For the high PA group, Design Quality exerted a notably stronger direct effect on Fascination (β = 0.128) and Being-away (β = 0.454). These qualities, in turn, contributed significantly to the perception of relaxation and stress reduction. This finding suggests that for individuals with stronger multidimensional bonds to the area—encompassing identity and dependence—streetscapes that offer engaging visual elements (Fascination) and a sense of escape from daily routines (Being-away) yield the highest psychological benefits.

Conversely, for the low PA group, the overall impact of Design Quality on restorative qualities was weaker. However, distinct patterns were observed: Design Quality contributed most positively to Scope (β = 0.134) and Being-away (β = 0.166), which subsequently influenced restorative outcomes. This indicates that populations with lower attachment prioritize streetscapes that are perceived as open and offer opportunities for exploration (Scope) to achieve restoration, rather than relying on the specific engaging details that drive the high PA group.

The direct pathway from Design Quality to Restorative Outcomes was significant for both groups, yet the magnitude differed substantially. The estimate for the high PA group (β = 0.740) was nearly double that of the low PA group (β = 0.387). This suggests that the baseline quality of the physical environment has a far more profound impact on the overall well-being of residents who are already attached to the place.

Mediation effects, detailed in Table 6, further reinforce this disparity. The total indirect effect was larger for the high PA group (β = 0.176) compared to the low PA group (β = 0.149), indicating that restorative qualities mediate the relationship between design and well-being more effectively for highly attached individuals. In summary, the high PA model consistently outperformed the low PA model across both direct and indirect pathways. High PA individuals appear to engage with a broader and more complex range of restorative qualities — emphasising fascination and mental escape — whereas low PA individuals rely on a narrower set of environmental cues, primarily centred on spatial scope and openness.

Table 6: Indirect effects of GSEM models of high PA and low PA groups. * indicates $p < 0.05$.

Path	**Standard Estimate (L)**	**Standard Estimate (H)**
DQ_Fascination_RO	-0.020*	0.016*
DQ_Scope_RO	0.046*	0.000*
DQ_Coherence_RO	0.054*	-0.008*
DQ_Being-away_RO	0.070*	0.167*
Total effect	0.149*	0.176*

5. Discussion

5.1. Applying ML-based framework for evaluating restoration perceptions

This study integrates street view imagery, machine learning, and survey data to demonstrate that Place Attachment (PA) is not merely an outcome of urban design, but a fundamental cognitive moderator that shapes how restorative potential is perceived. While existing literature often treats PA and restoration as parallel benefits of green space (Subiza-Pérez et al., 2020; Ratcliffe and Korpela, 2016), our findings suggest a more relational interpretation: place attachment can condition how restorative value is extracted from everyday urban form. In this sense, PA acts as a catalyst, amplifying the restorative benefits derived from physical urban features.

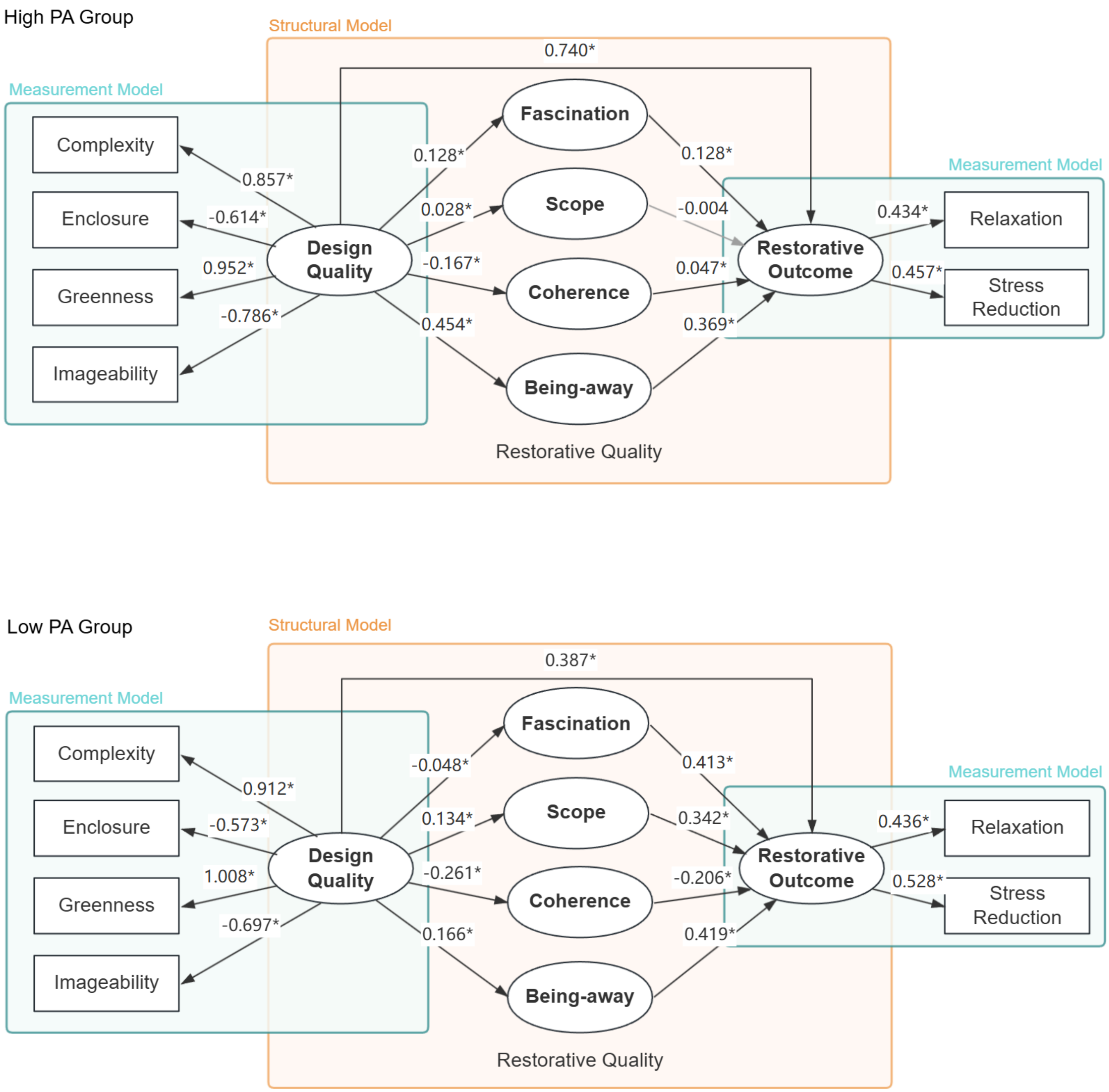

Figure 5: Generalized Structural Equation Model (GSEM) plot for high PA and low PA groups. The direct pathway effect from Design Quality and the total mediation effects to Restorative Outcomes were higher for the high PA individuals. * indicates $p < 0.05$.

Theoretically, this challenges the binary view that ”nature restores” and ”urban stressors deplete.” We found that for individuals with high PA, the urban fabric itself—imbued with functional reliance and symbolic meaning—becomes a source of restoration. This aligns with — and extends — the *meaning-mediated model* of restoration (Scannell and Gifford, 2010; Li et al., 2023b). By achieving 74% accuracy in predicting neighbourhood-specific restorativeness, our ML framework validates that restoration is not solely an intrinsic property of physical features (e.g., green density), but a product of the interaction between physical form and the observer's psychological connection to the place. This interpretation also resonates with concerns in urban studies that rapid urbanization and placeless development can weaken residents' bonds with their surroundings (Rollero and De Piccoli, 2010). Our findings suggest that such placelessness may reduce not only cultural identification, but also the restorative capacity of everyday urban environments.

5.2. The role of place attachment in bridging visual characteristics, design quality, and restoration

A key contribution of this study is the explication of how PA alters the processing of visual stimuli, evidenced by the divergent feature importance (SHAP) and psychological pathways (GSEM) between groups. This helps extend existing restorative research, which has largely identified which streetscape features are associated with restoration, but has less often examined for whom those same features become restorative.

For individuals with strong PA, restoration appears to be driven by symbolic immersion. Our SHAP analysis shows that these individuals derive restoration not only from vegetation but also from built features typically considered stressors, such as buildings and landmarks. This is consistent with studies showing that built environments are not necessarily detrimental to restoration when they convey coherence, architectural quality, familiarity, or personal meaning (Lindal and Hartig, 2013; Li et al., 2023b; Subiza-Pérez et al., 2021). The present findings extend this argument by suggesting that Place Identity can transform generic infrastructure into meaningful symbols of continuity, while Place Dependence makes those environments functionally supportive in daily life (Scannell and Gifford, 2010). Consequently, the GSEM results indicate that high-PA individuals access restoration especially through Fascination and Being-away. This supports the idea that ”soft fascination” need not be limited to natural settings (Kaplan and Kaplan, 1989); in dense urban contexts, it may also emerge from familiar and identity-bearing streetscapes.

Conversely, for individuals with low PA, restoration appears to be driven by structural legibility. This group relied heavily on generic structural elements (e.g., walls, roads, sky) and psychological constructs of Scope and Being-away. This finding is broadly compatible with previous streetscape studies showing that openness, coherence, and certain orderly urban elements can contribute positively to restorative appraisal, even when the environment is less green (Ma et al., 2024; Wu et al., 2024; Subiza-Pérez et al., 2021). We interpret this through the lens of Perceptual Fluency Theory (Reber et al., 2004) and Nasar's evaluative framework (Nasar, 1994). Lacking the "top-down" cognitive schema provided by Place Identity, Low-PA individuals (e.g., newcomers or transients) likely process the environment in a "bottom-up" manner. They prioritize spatial clarity, openness, and ease of navigation to reduce cognitive load. For this group, restoration appears to depend less on symbolic meaning and more on sense-making through form. This distinction suggests that restorative experience may operate through at least two partially overlapping processes: meaning-making for the attached, and sense-making for the less attached.

5.3. Spatial heterogeneity: The gap between New and Old districts

The spatial distribution of these perceptions highlights a critical equity issue in urban planning. Our analysis reveals that the perceptual gap in stress reduction is most pronounced in newer suburban developments. These areas, often populated by migrants or transient groups, lack the historical accretion that fosters deep Place Identity. This finding echoes previous work suggesting that familiarity and sense of place can buffer environmental stress and support well-being in urban neighbourhoods (Ng et al., 2022; Li et al., 2023b). In such contexts, residents are solely dependent on the physical quality of the environment (visual legibility) for restoration.

In contrast, older, established districts benefit from a "buffering effect." The shared cultural memory and long-term functional dependence associated with these areas appear to sustain restorative perceptions even when visual design quality varies. This is broadly consistent with studies showing that repeated use, memory, and emotional attachment can strengthen restorative responses (Korpela and Hartig, 1996; Korpela and Ylén, 2009; Ratcliffe and Korpela, 2016). It also resonates with research from other Global South contexts. For example, studies in Harare show that strong place attachment can persist in informal and materially constrained neighbourhoods, shaped by social ties, lived experience, and neighbourhood conditions rather than by environmental quality alone (Bandauko et al., 2022, 2024). Read together, these findings suggest that the restorative implications of place attachment may be especially relevant in cities where uneven development, residential mobility, and place disruption coexist.

At the same time, the results point to a vulnerability in newly developed areas. When new towns are designed without distinct character, social infrastructure, or functional logic, they may struggle to foster the attachment needed to unlock the fuller restorative potential of the urban environment. This does not mean that all new developments are inherently less restorative, but rather that, in weakly rooted urban contexts, restorative benefit may depend more strongly on whether environments can support both legibility and place-making over time. In this sense, the study speaks not only to Hong Kong, but also to other rapidly urbanising cities facing tensions between growth, mobility, and belonging.

5.4. Design and policy implications

These findings suggest that "one-size-fits-all" urban greening is insufficient. Consistent with recent work showing that restorative benefits depend on both environmental attributes and users' social-emotional relationships to place (Subiza-Pérez et al., 2020; Li et al., 2023b). Restorative design must be context-sensitive, responding to the specific attachment dynamics of the neighbourhood.

Designing for the Unattached (New Towns/Transit Zones). In areas with high residential turnover or low existing PA, design should prioritize *Perceptual Fluency*. Interventions should focus on visual coherence, clear wayfinding, and high-visibility greening (e.g., vertical gardens, distinct street trees) that requires little cultural knowledge to appreciate. The goal is to reduce the cognitive load of navigation and provide immediate sensory relief. Such strategies may be especially important in rapidly urbanising districts where residents have not yet developed strong local ties.

Designing for the Attached (Historic/Established Districts). In high-PA areas, restoration is linked to *Identity*. Planners should prioritize the preservation of symbolic landmarks, vernacular architecture, and social gathering spaces. Here, "messier" or more complex urban forms are acceptable—and even restorative—if they embody local history. Design guidelines should focus on protecting the "narrative" of the streetscape rather than just its aesthetic order.

Fostering Attachment as a Health Strategy. Finally, policy should view the cultivation of Place Attachment as a public health intervention. Participatory design processes, heritage conservation, and the creation of walkable social infrastructure can accelerate the transition from "space" to "place," thereby unlocking the deeper, identity-based restorative benefits for residents.

Beyond Hong Kong, these implications may be relevant to other Global South cities experiencing rapid urban expansion, uneven neighbourhood development, and high levels of residential mobility. In such settings, attachment cannot be assumed to arise automatically from physical upgrading alone. As the Harare studies suggest, strong place bonds may coexist with material deprivation, while newly developed or weakly rooted areas may remain psychologically thin despite formal planning (Bandauko et al., 2022, 2024). This means that restorative planning in the Global South should not focus only on adding greenery or improving visual quality, but also on sustaining local identity, everyday functionality, and social rootedness in ways that are sensitive to different urban trajectories.

5.5. Limitations and future work

This study has several limitations. First, the sample comprises Hong Kong residents; while appropriate for the study area, it may not represent perceptions in other cultural and urban contexts. In addition, because the data are cross-sectional, the study cannot fully capture how restorative experiences and place attachment may evolve over time. Future research could employ longitudinal designs to investigate whether repeated everyday exposure to restorative urban environments generates cumulative benefits and contributes to the longer-term formation of place attachment.

Second, place attachment was measured at the district level, while restorative perceptions were rated for specific street view images within those districts. This is consistent with the view of place attachment as a contextual neighbourhood relationship, but future work could refine this approach by examining more localised forms of attachment at the neighbourhood or street-segment level. Such an extension would help clarify how attachment to finer-grained urban contexts moderates the relationship between design quality and restorative perception.

Third, although the SVI dataset used in this study is extensive, street view imagery inevitably provides a selective representation of urban environments and may not fully reflect the entire diversity of streetscapes across Hong Kong (Chen and Biljecki, 2023). More broadly, SVI is particularly well suited to capturing visually observable street environments at scale, but it is less able to represent the dynamic and multisensory dimensions of urban experience, including pedestrian immersion, temporal variability, and non-visual factors such as sound, thermal comfort, smell, and crowding, all of which may also shape restorative experience (Weber and Trojan, 2018). Future research could therefore extend this approach by combining SVI with pedestrian-level, temporal, and in-situ data, and by drawing on multimodal or neuro-urbanism approaches, to provide a more comprehensive account of restorative urban experience (Adli et al., 2017; Asim et al., 2023; Dong et al., 2025).

In addition, although the overall machine learning performance was robust, variation across perceptual dimensions suggests that some subjective restorative responses are more heterogeneous and therefore less readily predictable than others. Future research may further improve predictive performance by incorporating richer visual and contextual features, expanding labelled samples, and exploring modelling approaches that better capture spatial context and inter-scene relationships.

6. Conclusion

This study examines the neglected but important interplay between place attachment, restorative quality, and restorative outcomes in urban environments. By employing a framework utilizing street view imagery, the study reveals that restorative perceptions are shaped not only by the visual characteristics of streetscapes, but also by the extent to which people are emotionally and functionally connected to place. It identifies significant spatial and social disparities in restorative perceptions across different place attachment groups, thereby extending current understanding of restorative urban environments beyond the physical attributes of design alone.

The key findings are as follows: (1) individuals with higher place attachment in general perceive higher restorative quality and psychological benefits than their low-PA counterparts; (2) natural elements, particularly vegetation and sky, contribute more to predicting restorative perceptions for high PA groups, low PA individuals prioritize semantic segmentation features related to enclosure and urban structures (e.g., walls, sidewalks); (3) spatial differences between high- and low-PA groups are more pronounced in suburban areas in Hong Kong (especially new towns); (4) restorative quality positively mediates the impact of design quality on restorative outcomes, with the mediation effect being stronger in the high PA group. Taken together, these findings suggest that the restorative value of urban streets is not universal or socially neutral. Rather, it is relational: the same physical environment may be interpreted differently depending on residents' attachment to place.

This study therefore provides the first city-scale comparative evidence that place attachment moderates the visual drivers of restoration. More importantly, it suggests that restorative planning should move beyond one-size-fits-all assumptions. In areas where attachment is weak or still emerging, improving legibility, openness, and visible environmental comfort may be especially important. In contrast, in neighbourhoods where attachment is already well established, preserving meaningful local identity, familiar landmarks, and socially embedded streetscape qualities may be more consequential for psychological recovery. This implies that fostering mental health through urban design is not only a matter of improving physical form, but also of supporting the social and symbolic processes through which urban space becomes psychologically meaningful. Future research should further explore the role of restorative outcomes in multi-sensory urban settings. Integrating sensory and in-situ data, along with neuro-urbanism approaches (Asim et al., 2023; Adli et al., 2017), could offer a more comprehensive understanding of how urban environments support psychological recovery.

CRediT authorship contribution statement

Sifan Cheng: Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Qiwei Song:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. **Xiucheng Liang:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Pu Jiang:** Writing – review & editing, Resources. **Filip Biljecki:** Writing – review & editing, Supervision, Resources, Conceptualization. **Jeroen van Ameijde:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization.

Declaration of competing interest

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

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Data availability

The authors do not have permission to share data.

Appendix A. Supplementary information on the survey

Table A.7: Population distribution of the participants of the online survey.

Group	Population
Total	547
Female	288
Male	255
Prefer not to say	4
18-24	78
25-34	63
35-44	111
45-54	82
55-64	98
65+	115
High place attachment	219
Moderate place attachment	103
Low place attachment	225

Table A.8: Reliability and Validity of online survey data.

		Fascination	Scope	Coherence	Being-away	Relaxation	Stress Reduction
High PA	Cronbach's Alpha	0.888	0.922	0.766	0.921	0.928	0.830
	KMO	0.929	0.828	0.782	0.874	0.866	0.852
	ICC	0.934	0.877	0.874	0.920	0.901	0.918
Low PA	Cronbach's Alpha	0.945	0.871	0.837	0.890	0.916	0.927
	KMO	0.809	0.797	0.560	0.751	0.749	0.781
	ICC	0.921	0.897	0.824	0.935	0.937	0.965

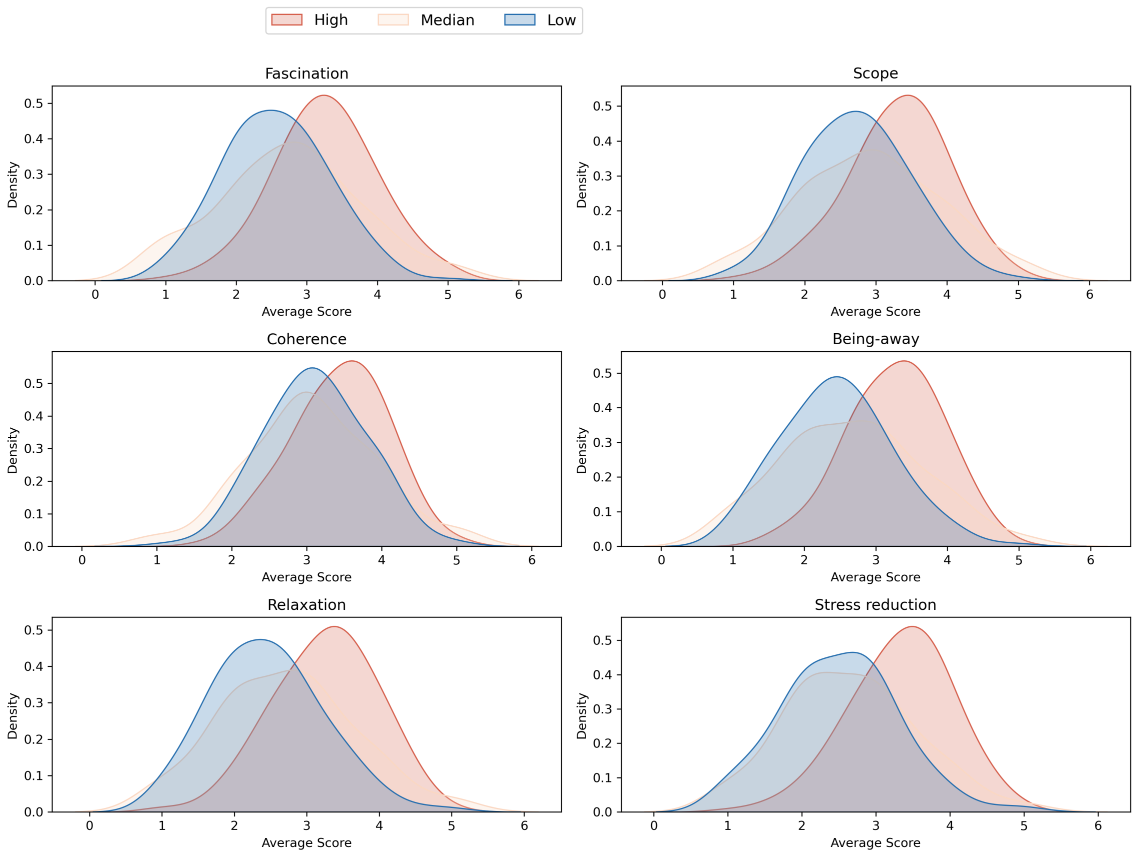

Figure A.6: The distribution plot of place attachment scores from the survey data, segmented into high PA, middle 20%, and low PA population groups.

Table A.9: Train and Test Dataset for XGBoost Classification Models.

Model	**0**	**1**	**2**
High PA			
Train	56	253	142
Test	23	108	61
Low PA			
Train	136	270	46
Test	57	114	21

Appendix B. Supplementary materials on parameters calculations

Appendix B.1. Design qualities

Appendix B.1.1. Imageability

Imageability captures the visual elements that contribute to the recognizability and distinctiveness of the urban environment. It is calculated as the sum of the visual indices of buildings and signs:

$$\mathrm{Img}_i = VI_{\mathrm{bldg},i} + VI_{\mathrm{sign},i} \tag{B.1}$$

where Img_i denotes the imageability index for observation i, $VI_{\mathrm{bldg},i}$ denotes the visual index of buildings, and $VI_{\mathrm{sign},i}$ denotes the visual index of signs.

Appendix B.1.2. Complexity

Complexity reflects the richness and diversity of urban elements in a scene. It is calculated as the proportion of people, billboards, vegetation, and traffic signs to the built environment (buildings and roads):

$$\mathrm{complex} = \frac{VI_{\mathrm{person}} + VI_{\mathrm{billboard}} + VI_{\mathrm{veg}} + VI_{\mathrm{sign}}}{VI_{\mathrm{building}} + VI_{\mathrm{road}}} \tag{B.2}$$

where:VI_{person}: Person, $VI_{\mathrm{billboard}}$: Billboard, VI_{veg}: Vegetation, VI_{sign}: Traffic Sign (Front), VI_{building}: Building, VI_{road}: Road

Appendix B.1.3. Greenness

Greenness measures the extent of vegetation in the scene, providing an indicator of natural elements in urban areas:

$$\mathrm{green} = VI_{\mathrm{veg}} \tag{B.3}$$

where:VI_{veg}: Vegetation

Appendix B.1.4. Enclosure

Enclosure represents the degree to which spaces are visually defined by physical boundaries. It is calculated as the ratio of enclosing elements (buildings, mountains, walls, and barriers) to the total area of roads and sidewalks:

$$\mathrm{enclo} = \frac{VI_{\mathrm{building}} + VI_{\mathrm{mountain}} + VI_{\mathrm{wall}} + VI_{\mathrm{barrier}}}{VI_{\mathrm{road}} + VI_{\mathrm{side}}} \tag{B.4}$$

where:VI_{building}: Building, VI_{mountain}: Mountain, VI_{wall}: Wall, VI_{barrier}: Barrier, VI_{road}: Road, VI_{side}: Sidewalk

Appendix C. Supplementary materials on ML evaluation

For multi-class evaluation, Macro-Accuracy (Macro-ACC) and Macro-F1 score were calculated, treating each class equally, which is beneficial for imbalanced datasets:

$$\text{Macro-ACC} = \frac{1}{C}\sum_{i=1}^{C}\frac{\text{TP}_i}{\text{TP}_i + \text{FP}_i + \text{FN}_i} \tag{C.1}$$

$$\text{Macro-F1} = \frac{1}{C}\sum_{i=1}^{C}\frac{2\text{TP}_i}{2\text{TP}_i + \text{FP}_i + \text{FN}_i} \tag{C.2}$$

where C represents the total number of classes, in our case 3. TP_i denotes the true positives for class i, FP_i refers to the false positives for class i, while FN_i is the wrongly predicted negatives, i.e., false negatives for class i.

Table C.10: Model prediction performance for high PA and low PA groups.

Model	**High PA**		**Low PA**	
	ACC	**F1**	**ACC**	**F1**
Decision Tree (DT)	0.61	0.52	0.61	0.51
Gradient Boosting (GB)	0.63	0.52	0.64	0.50
AdaBoost	0.64	0.51	0.63	0.51
Random Forest	0.67	0.54	0.69	0.52
LightGBM	0.64	0.52	0.65	0.51
XGBoost	**0.76**	**0.71**	**0.74**	**0.70**

Appendix D. Supplementary materials on SHAP value

SHAP assigns a "SHAP value" to each feature for every prediction, quantifying its contribution. The sum of these SHAP values explains the model's output. The feature contributions are mathematically represented as follows:

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

where $g(z)$ is the predicted output, ϕ_0 is the base value, ϕ_j represents the SHAP value for feature j, and z_j is the corresponding feature.

Appendix E. Supplementary materials on GSEM

Table C.11: XGBoost model performance across restorative dimensions for high PA and low PA groups, using SMOTE.

Metric	Group	ACC	F1	MAE	RMSE
Fascination	H	0.808	0.755	0.550	0.834
	L	0.678	0.632	0.588	0.809
Scope	H	0.758	0.761	0.621	0.899
	L	0.706	0.684	0.578	0.815
Coherence	H	0.733	0.666	0.534	0.776
	L	0.759	0.701	0.495	0.749
Being-away	H	0.771	0.680	0.587	0.858
	L	0.772	0.735	0.630	0.900
Relaxation	H	0.754	0.698	0.554	0.789
	L	0.771	0.740	0.629	0.856
Stress Reduction	H	0.735	0.687	0.515	0.758
	L	0.771	0.734	0.548	0.814

Table E.12: GSEM model performances of high PA and low PA groups.

Model metrics	Low PA model	High PA model	Overall model
CFI	0.826	0.970	0.895
TLI	0.739	0.955	0.865
RMSEA	0.116	0.052	0.058
SRMR	0.117	0.053	0.064

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