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Running in Rotterdam's blue spaces: Age group preferences and the impact of visual perceptions

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ABSTRACT

The increasing recognition of the health benefits of blue spaces highlights their crucial role in constructing Healthy Cities and advancing Sustainable Development Goals. Given that promoting recreational running represents a fundamental pathway to harnessing these benefits, integrating it into spatial planning and design is imperative. Nevertheless, this integration process necessitates substantiated evidence, especially concerning variances among population groups. To address this gap, utilising crowdsourced data and a machine learning approach, this study investigates heterogeneous spatial distributions of recreational running across various age demographics in Rotterdam, with a specific emphasis on visual perceptions and built environments. The mapping results illustrate the varied allure of blue spaces for recreational running, exhibiting a trend of increased clustering in running activities with age, extending beyond the city centre. The outcomes of GWR and spatial regression models indicate significant associations between various visual perception factors and built environment indicators with individual running preferences. Crucially, disparities and spatial heterogeneity are evident in the impacts of different environmental factors on running across age groups. Accordingly, tailored planning strategies and patterns are proposed, informed by age-specific environmental perceptions and preferences, contributing to a deeper understanding of the blue-health mechanism and offering practical insights for creating health-promoting blue spaces.

1. Introduction

As rapid urbanisation and global population growth continue, it is anticipated that by 2030, over 60 % of the world's inhabitants will reside in urban areas (Rydin et al., 2012). This population concentration has exacerbated various urban problems such as air pollution, traffic accidents, noise pollution, and heat islands (Heaviside et al., 2017; Sicard et al., 2023; Stansfeld et al., 2000). Urban scholars globally agree that urban environments significantly contribute to contemporary health challenges, particularly chronic non-communicable diseases and mental health issues (Harpham, 2009; Salgado et al., 2020). Consequently, urban health has become a policy priority in the current urbanisation agenda. Addressing the health needs of the expanding urban population is imperative and aligns with the Healthy City Initiative and the Sustainable Development Goals (SDGs) (Duhl & Sanchez, 1999; UN General Assembly, 2015; WHO, 2020).

An increasing body of research indicates that exposure to urban natural environments significantly benefits human health (Hartig et al., 2014; Hartig & Kahn, 2016; Triguero-Mas et al., 2015). Widely discussed concepts such as ecosystem services and nature-based solutions underscore the considerable potential and practicality of utilising natural environments to tackle contemporary health challenges (Bratman et al., 2019; Fang et al., 2024). Urban natural environments help mitigate the negative impacts of noise and pollution, providing a calming atmosphere that alleviates environmental stressors in fast-paced urban lives. Studies indicate that cognitive functions benefit from natural environments, as they aid in restoring attention and reducing mental fatigue (Bratman et al., 2015; Zijlema et al., 2017). On the other hand, physical activity is a crucial pathway for realising the health benefits of natural environments (Hartig et al., 2014; Hunter et al., 2023). By offering safe and comfortable spaces, urban natural areas encourage residents to engage in physical activities, reducing the risk of chronic diseases such as obesity, cardiovascular diseases, and diabetes (Remme et al., 2021; Sallis et al., 2016). Furthermore, urban natural environments promote social interactions, fostering community cohesion and social support, which are essential for human health (Peters et al., 2010;

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Rasidi et al., 2012).

Despite ample evidence of the health benefits of urban natural environments, significant research gaps remain. First, existing studies have primarily focused on green spaces, while blue spaces - critical components of urban natural environments - are increasingly attracting interest from researchers and practitioners (Grellier et al., 2017; Zhang, Nijhuis, & Newton, 2022). Established mechanisms linking blue spaces to health include enhancing physical activities (Boakye et al., 2021; Gascon et al., 2017), improving ambient physical environments (White et al., 2020), providing psychological benefits (Gidlow et al., 2016; MacKerron & Mourato, 2013), and fostering social interactions (de Bell et al., 2017). Among them, enhancing physical activities, such as recreational running, is the most prevalent and has garnered considerable academic attention, showing significant potential for practical application. Researchers have used multi-scale data and techniques to identify blue space elements that significantly influence recreational physical activities, offering crucial insights for policy-making and spatial interventions (Perchoux et al., 2015; White et al., 2014). However, although several practical methods have been identified to evaluate the effectiveness of these strategies (Wang et al., 2021; Zhang et al., 2023a, 2023b), more empirical evidence is needed.

Second, identifying the comprehensive factors influencing people's willingness to engage in physical activity in blue spaces remains challenging. Spatial distance is increasingly recognised as not the sole influencing factor, while various other elements also play crucial roles, including individual perceptions of blue spaces, types of blue spaces, spatial quality, and local culture (McDougall et al., 2020; McDougall et al., 2022; White et al., 2020). Among them, environmental perception characteristics from eye level are deemed critical factors influencing physical activities, garnering growing research attention (Liu et al., 2023; Wang et al., 2016). Notably, for these factors to be integrated into planning processes similarly to spatial distance, their relationship with physical activity needs thorough exploration to develop targeted spatial strategies, aligning with the knowledge/evidence-based design paradigm (Brown & Corry, 2011).

Third, few studies have focused on age differences in the impact of environmental factors on physical activity, despite evidence that environmental preferences vary by socio-economic characteristics. Recent research indicates that individuals across different age groups exhibit distinct environmental perceptions and preferences for running, which is particularly crucial for vulnerable older populations with limited running opportunities (Laddu et al., 2021). This underscores the necessity for more comprehensive evidence to address the physical activity needs of these groups, supporting efforts to eradicate inequalities in health-promoting opportunities. Importantly, there is a need to explore translating detailed empirical findings into context-based refined spatial intervention strategies, which have been identified as a critical gap and urgent action (WHO, 2021; Zhang, Nijhuis, & Newton, 2022).

With advancements in emerging technologies and diverse geo-tagging data sources, analysing the relationship between individuals' running preferences and detailed environmental characteristics at the city/population level has become feasible. The combination of computer vision techniques and large-scale street view images (SVIs) offers an efficient and effective approach to evaluating and understanding environmental features from eye level, as demonstrated in several studies (Biljecki & Ito, 2021; Kang et al., 2020). Trajectory data on physical activity (e.g., running, cycling) collected through GPS, PPGIS, and Volunteer Geographic Information (VGI) can directly depict individuals' activities in urban settings, providing a foundation for comprehending human behaviour. The low cost and absence of additional equipment requirements in VGI data make it a promising tool for integration with large-scale SVI data to understand the interplay between human behaviour and environmental preferences (Dong et al., 2023; Huang, Kyttä, et al., 2023; Zhang et al., 2024).

Therefore, to address the aforementioned research gaps and gather detailed evidence for targeted planning and design strategies, this study aims to investigate the correlation between various spatial characteristics of blue spaces, with a particular focus on visual perception factors and the various levels of recreational running among diverse age groups, as well as provide a set of multi-level spatial intervention strategies to support the development of running-promoting blue spaces (Fig. 1). Specifically, building upon VGI, SVI, and POI data in Rotterdam, this research addresses three key questions: (1) What spatial characteristics of blue spaces, particularly visual perception, are correlated with individuals' engagement in recreational running? (2) Does the relationship between these spatial characteristics and recreational running vary among different age groups? (3) How can the results of the analysis contribute to future planning and design practices? Based on these analyses, this study aims to advance healthy city studies and practices by providing a detailed and systematic understanding of the heterogeneous effects of urban blue spaces on recreational running across different age groups.

The remainder of this paper is organised as follows: Section 2 introduces the data sources, processing and methodology; Section 3 illustrates the analysis results; Section 4 discusses and Section 5 concludes.

2. Research data and methods

2.1. Study area and study design

Rotterdam was chosen as the study area to investigate the relationship between blue space spatial characteristics and recreational running across various age groups. As the second-largest city in the Netherlands, Rotterdam holds strategic importance as a major European port. It is located in the province of South Holland, characterised by a temperate oceanic climate. Covering an area of 326 km^2, Rotterdam has a population of over 6 million in 2022 (CBS, 2023). As a commercial and industrial centre along the Nieuwe Maas River, much of the city is situated on riverbanks, polders, and reclaimed land, with a substantial portion of the city lying below sea level (Frantzeskaki & Tilie, 2014). Consequently, Rotterdam boasts extensive experience in water management and possesses abundant blue space resources, encompassing various natural and artificial water bodies. These blue spaces allow urban residents to engage in recreational running and other physical activities as part of their daily lives. Furthermore, the Netherlands has cultivated a robust running culture, establishing it as a popular form of daily exercise (Vink & Varró, 2021).

The research framework consists of seven steps (Fig. 1). First, the street-level recreational running counts of blue spaces among different age groups were obtained from the Strava. Secondly, the visual perception factors of blue spaces were computed through the pixel ratio of various elements based on the Street View Images (SVIs) for each sample point on street segments within blue spaces. Thirdly, factors

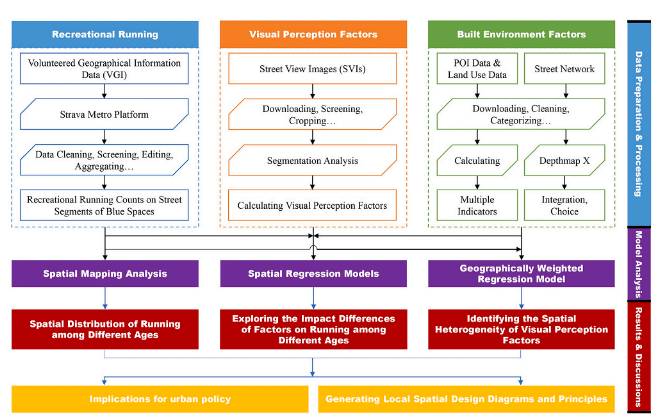

Fig. 1. Research framework.

from multiple sources were collected, including built environments and contextual factors which could influence recreational running. Fourth, mapping analysis was conducted to understand the spatial distribution of recreational running in blue spaces among various age groups. Fifth, the GWR model was employed to investigate the spatial distribution heterogeneity of visual perception factors influencing recreational running. Subsequently, OLS and spatial regression models were utilised to examine the correlations between environmental factors and recreational running across various age groups. Finally, considering the distinct spatial perceptions and preferences of different age groups regarding running in blue spaces, the study proposed tailored planning strategies and patterns derived from the analysis results.

2.2. Data sources

2.2.1. Dependent variables: the recreational running counts among different age groups at street segments

The street-level recreational running data for various age groups is derived from VGI data of the Strava Metro platform, encompassing the entire year of 2021. Strava, a GPS-based mobile fitness app boasting over 1 billion registered users, is widely embraced in Western countries, including the Netherlands, where individuals regularly upload their daily physical activity data. In particular, the recreational running data is adopted to determine the intentional health-oriented activity, distinguishing it from other types of running behaviour, such as commuting running. Following anonymising personal information, the recreational running track data aggregates into distinct street segments within Rotterdam, subsequently summarised according to four main age groups (i.e. 18–34, 35–54, 55–64, 65plus). The foundational dataset for modelling the streets of Rotterdam is derived from the OpenStreetMap (OSM) database. Given the study's emphasis on blue spaces, the quantities of recreational running along streets proximate to blue spaces are selected as the dependent variable of this research. 50-meter buffers calculated around water bodies serve as a tool for the targeted street selection. Ultimately, a total of 24,050 streets, encompassing 35,685,390 running records, are purposively selected as the sample for the analysis.

2.2.2. Covariables at the street segment level: environmental predictors

2.2.2.1. Visual perception factors. Individuals' visual perception of surrounding environments could be a critical factor influencing their preferences for running and walking (Liu et al., 2023). In particular, for blue space, it has been proved that water visibility (Nutsford et al., 2016) and facilities in blue space (Garrett et al., 2019) are related to people visiting regularly. On the other hand, considering the more or less similar mechanism of blue space and green space in encouraging outdoor activities, broader and typical visual perception measurement of urban environment examined in extant urban green space studies, including the Green View Index (GVI), openness, building elements in view, on-land facilities in view, traffic elements in view, and visual complexity are also included in this study (Ma et al., 2021; Wang & Zhao, 2017; Xiang et al., 2022). The acquisition and calculation of each factor predominantly rely on combining SVIs and emerging deep learning techniques, aiming to depict the blue space environments at eye level precisely. The analytical process encompasses three primary steps (Fig. 2). Initially, the study establishes sampling points at 30-meter intervals, acquiring SVIs of the corresponding locations by using Python scripts and Google Street View API. Approximately 37,000 street view images are collected, covering the entirety of the streets of blue spaces, and subsequently subjected to cropping to mitigate image distortion. Next, leveraging existing research outcomes, the study employs a pre-trained model rooted in the fully convolutional network (FCN-8 s) and the ADE20K database to execute semantic segmentation on the collected SVIs (Helbich et al., 2019). Finally, guided by the segmentation outcomes, the visual perception factors associated with an individual SVI are computed through the proportional representation of each element in the total pixel count of the image (Table 1). Building upon this, the study aggregates the average of the analysis outcomes from multiple SVIs corresponding to each street, establishing it as the ultimate value for the visual perception factors on the street.

2.2.2.2. Built environment factors. Apart from visual perception factors, this study incorporates a series of factors related to built environments influenced by existing evidence that may impact individuals' engagement in recreational running. Specifically, the study introduces the choice and integration value, calculated through Space Syntax, to characterise road connectivity. These two factors are posited to influence individuals' running route selection significantly. On the other hand, the land-use patterns and distribution of surrounding facilities can influence individuals' evaluations and experiences of the ambient environments, leading to varied behavioural choices. Accordingly, six factors are included in the analysis, including the count of bus stops, tram stops, sports facilities, cultural facilities, restaurants/cafes, and land use mix, within a 50-meter radius of the corresponding street (Table 1). The facility number of the street mainly relies on the Point of Interest (POI) data available in the OSM database, while the land use data is retrieved from the Dutch Centraal Bureau voor de Statistiek (CBS) (CBS, 2023). Moreover, although NDVI is commonly used to assess

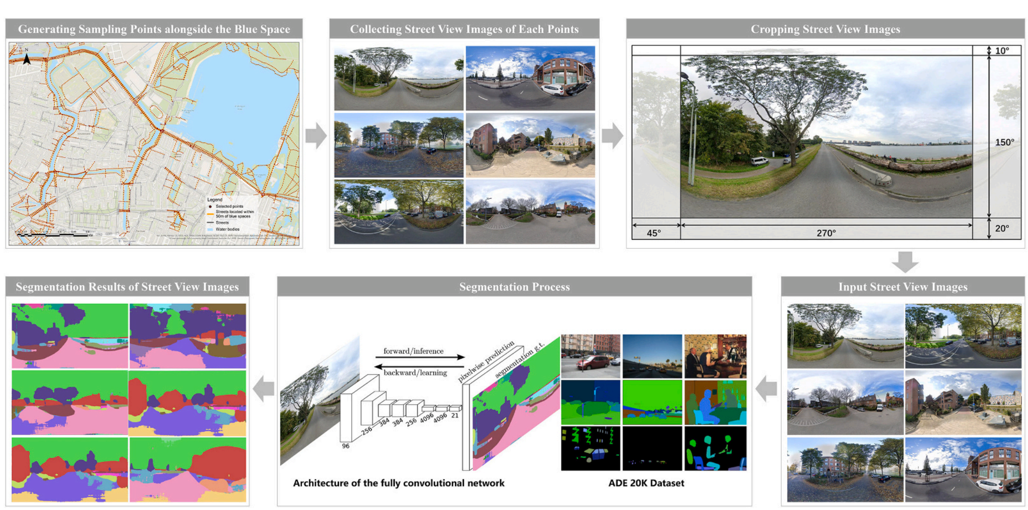

Fig. 2. The workflow of measuring visual perception factors of blue spaces in the study. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Definitions and descriptive statistics of all variables.

Variables	Definition	Mean	S.D.
Frequency of recreational running			
18–34	The recreational running intensity for participants aged 18–34 years	286.52	658.32
35–54	The recreational running intensity for participants aged 35–54 years	223.45	486.07
55–64	The recreational running intensity for participants aged 55–64 years	40.07	80.83
65plus	The recreational running intensity for participants aged over 65 years	12.15	20.66
Visual perception factors			
Water View Index (WVI)	The percentage of water bodies in view at locales	0.044	0.045
On water facilities	The percentage of on-water facilities in view at locales	0.002	0.004
Green View Index (GVI)	The percentage of vegetation in view at locales	0.121	0.091
Openness	The percentage of the sky in view at locales	0.301	0.126
Building elements	The percentage of building elements in view at locales	0.471	0.296
On land facilities	The percentage of on-land facilities in view at locales	0.01	0.012
Traffic elements	The percentage of traffic-related facilities in view at locales	0.009	0.013
Visual complexity	The number of visual components in view at locales	4.756	1.757
Built environments factors			
Choice	The likelihood of a street segment being traversed on all shortest routes from all streets to all other streets	0.89	0.28
Integration	The proximity of each street segment to all others based on the sum of angular changes made along each route	5942.21	1204.06
Land Use Mix	The number of different land use types with 100 m buffer at locales	3.08	1.26
Bus Stations	The number of bus stations within the 500 m buffer at locales	4.92	3.83
Tram Stations	The number of tram stations within the 500 m buffer at locales	2.18	3.24
Sport Facilities	The number of sport facilities within the 500 m buffer at locales	15.32	25.93
Cultural Areas	The number of cultural facilities within the 500 m buffer at locales	0.77	1.91
Restaurant & Cafe	The number of restaurants and cafes within the 500 m buffer at locales	6.92	18.02
Service Facilities	The number of community centres within the 500 m buffer at locales	0.17	0.44
Contextual variables			
Urbanicity	The urbanisation level of the neighbourhood, determined by the local ranking rules of Statistics Netherlands	1.59	0.98
Non-western Population	The percentage of non-western populations within the neighbourhood	0.30	0.16
Low-income Population	The percentage of the low-income population within the neighbourhood	9.46	5.58

urban greenery from an overhead perspective in environment-behaviour research, this study chose to exclude it in favour of the GVI, which describes greenery exposure at eye level. This decision is supported by evidence that eye-level measurements offer more accurate and robust assessments, as confirmed by sensitivity analyses detailed in the supplementary materials (Huang et al., 2022; Lu et al., 2019).

2.2.3. *Social compositional variables: demographic and socio-economic factors*

At the neighbourhood scale, three variables are employed to characterise and control the urban development and social contexts: urbanicity, the percentage of the non-Western population, and the percentage of low-income households. Existing research indicates that these neighbourhood-level factors significantly explain the characteristics and behaviours of local residents, rendering them commonly employed in current human behavioural and preference studies. All three factors are derived from the open-published database by CBS and classified by the unique code of neighbourhoods. Their measurements are also based on the official approaches of the Rotterdam municipality.

2.3. *Analysis methods*

The level of recreational running on the streets is assessed by considering various environmental factors, as described above. Four models, including ordinary least squares (OLS), geographically weighted regression (GWR), spatial lag regression (SLM), and spatial error regression (SEM), are employed to assess the environmental factors' impact on recreational running. Before fitting the models, a multicollinearity test is conducted on the independent variables. The variance inflation factor (VIF) results are all below 4.0, indicating that multicollinearity is not a significant issue. Additionally, due to the heteroscedasticity of the residuals, logarithmic transformations are applied to the dependent variables in four models.

It is imperative to address the issue of spatial heterogeneity when analysing behavioural data, as the OLS model assumes a spatially static correlation between running counts and their environmental determinants (Maroko et al., 2009). Prior studies have demonstrated that estimates of these correlations may display notable spatial variation, a phenomenon particularly evident in environmental behaviour studies (Dong et al., 2023; Huang, Kyttä, et al., 2023). Hence, the GWR model is employed to scrutinise the heterogeneity in the spatial distribution of environmental factors influencing recreational running. In particular, this study integrates multi-age running data to investigate spatial variations in the directional impact of visual perception factors across different regions. The GWR model applies a spatial weight function for the areas, employing the Gaussian function as the weight function to determine the optimal bandwidth based on the Corrected Akaike Information Criterion (AIC) (Tian et al., 2024).

On the other hand, for the specific correlations, the OLS model was first fitted in R Studio due to its easy interpretability. This model explores the relationship between variations in environmental factors within each unit and the corresponding changes in the recreational running of all age groups. Nevertheless, prior studies suggest that the spatial autocorrelation effect inherent in physical activity counts may introduce bias in OLS model results, as it assumes spatial independence of the dependent variable and its residuals. The Moran's I test is conducted in this research to evaluate the existence of spatial dependence effects, and the result indicates a pronounced autocorrelation between the amount of recreational running and its error term among adjacent streets (Moran's $I = 0.332$, $p = 0.001$). Therefore, the two spatial regression models, including the spatial lag regression model and the spatial error regression model, are fitted in this study through R Studio. Specifically, the spatial lag regression model assumes that the dependent variables in some regions are influenced by those in neighbouring areas. In contrast, the spatial error regression model assumes that the error terms of the dependent variables are spatially correlated (Ward &

Gleditsch, 2019). Generally, Lagrange Multiplier tests are used to choose between the SLM and SEM models. Considering the study's focus on analysing variations in environmental factors influencing running across different age groups, the outcomes of the two models are presented for comparative analysis. Both spatial models employ a weight matrix with a distance threshold of 150 m, selected based on two key considerations. Firstly, this threshold is consistent with the scale of Rotterdam's streets and aligns with findings from other city-scale studies (Troy et al., 2016). Secondly, a sensitivity analysis of various modelling distances was conducted, starting from 50 m and increasing in 25 m increments, to determine the most appropriate distance (detailed in the supplementary materials). This analysis, which involved evaluating the Akaike Information Criterion (AIC) for each threshold, indicated that AIC values begin to stabilise between 125 m and 175 m, suggesting diminishing returns in model performance beyond these thresholds. Thus, a threshold of 150 m was deemed suitable for the modelling weight matrix, considering both two aspects.

3. Results

3.1. Descriptive results and mapping analysis

Fig. 3 [1] directly illustrates the overall recreational running counts and their spatial distribution for the street segments of blue spaces in Rotterdam. Based on the overall spatial distribution of recreational running across all age groups, there is a heightened concentration of running activities on the streets on the northern bank of the Nieuwe Maas River. Compared to the streets in distant Rotterdam areas, the centre area attracts more recreational running. Moreover, upon closer investigation of the spatial patterns, the study identified streets with a higher count of recreational running, particularly in proximity to large-sized blue spaces, such as the streets along the Nieuwe Maas River and the Kralingen Lake.

Fig. 3 [1–4] shows the spatial distribution of recreational running counts at the street level among various age groups. In general, the middle-aged (34–64) and elderly (65plus) groups demonstrate similar

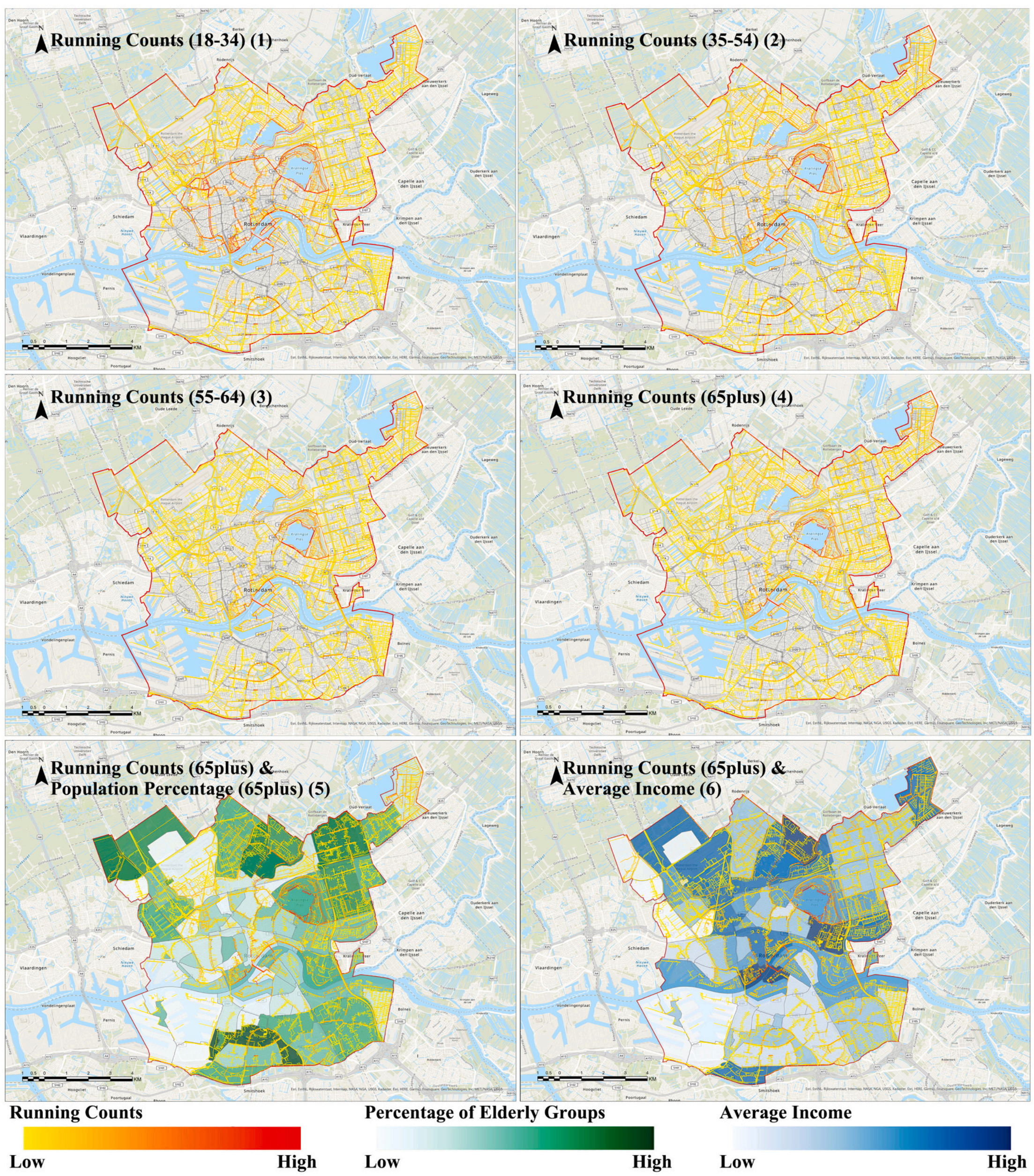

Fig. 3. The spatial distribution of recreational running among various age groups in Rotterdam.

spatial distribution patterns of recreational running along blue spaces, such as limited hot-running streets located in the northwest areas of the Nieuwe Maas River's north bank. As age increases, there are concentrations of spatial distribution for recreational running, primarily centred around the middle of the Nieuwe Maas River and the vicinity of the Kralingen Lake. Comparatively, the hot-running streets for the younger generation (18–34) are more spatially dispersed, which could be observed throughout Rotterdam. On the other hand, the utilisation of blue spaces located outside the city for recreational running is higher among the elderly (65plus) compared to other groups, particularly evident in communities situated in the northeast area of Rotterdam. Additionally, the overlapping analysis of the demographic compositions

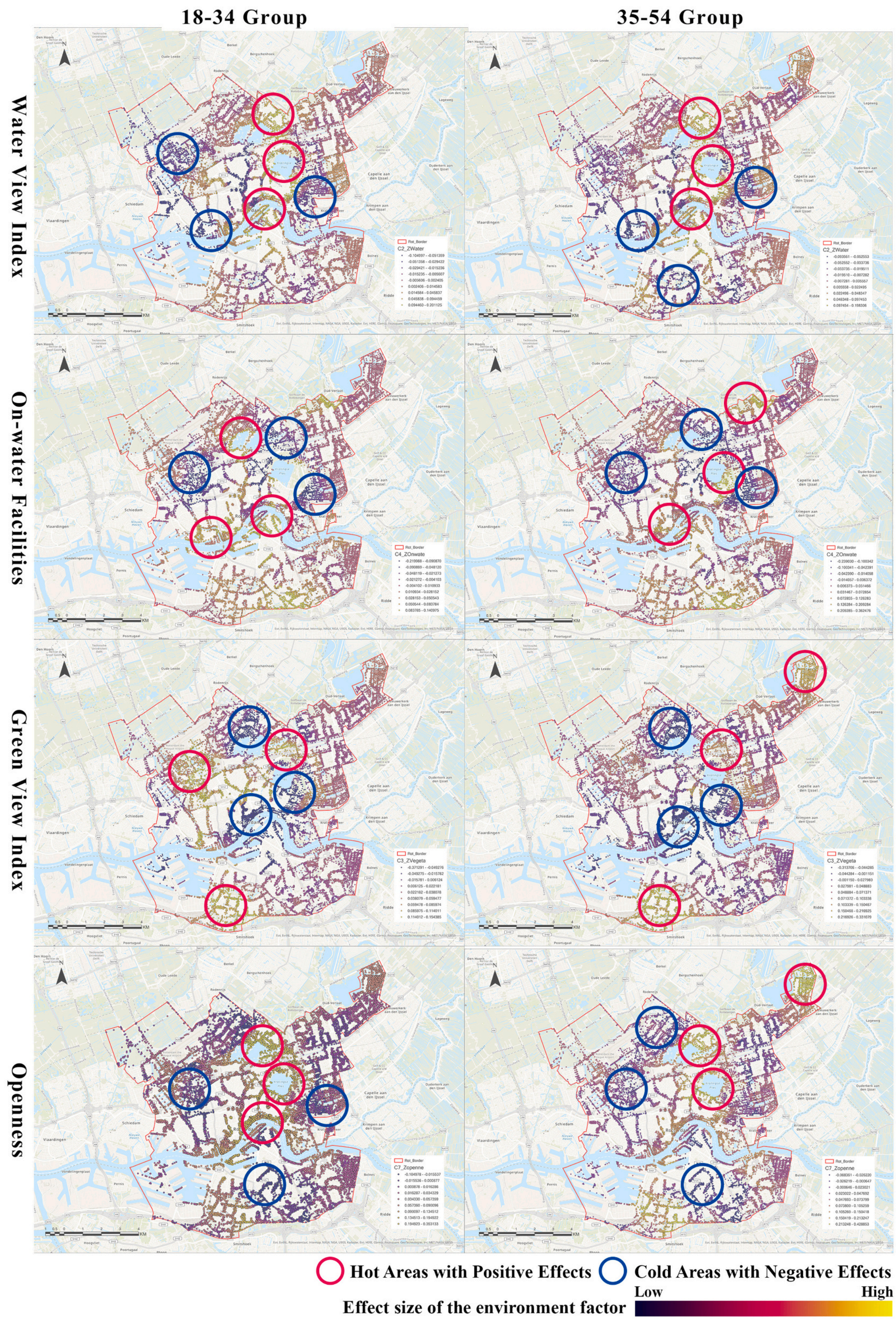

Fig. 4. The key results of the GWR model analysis.

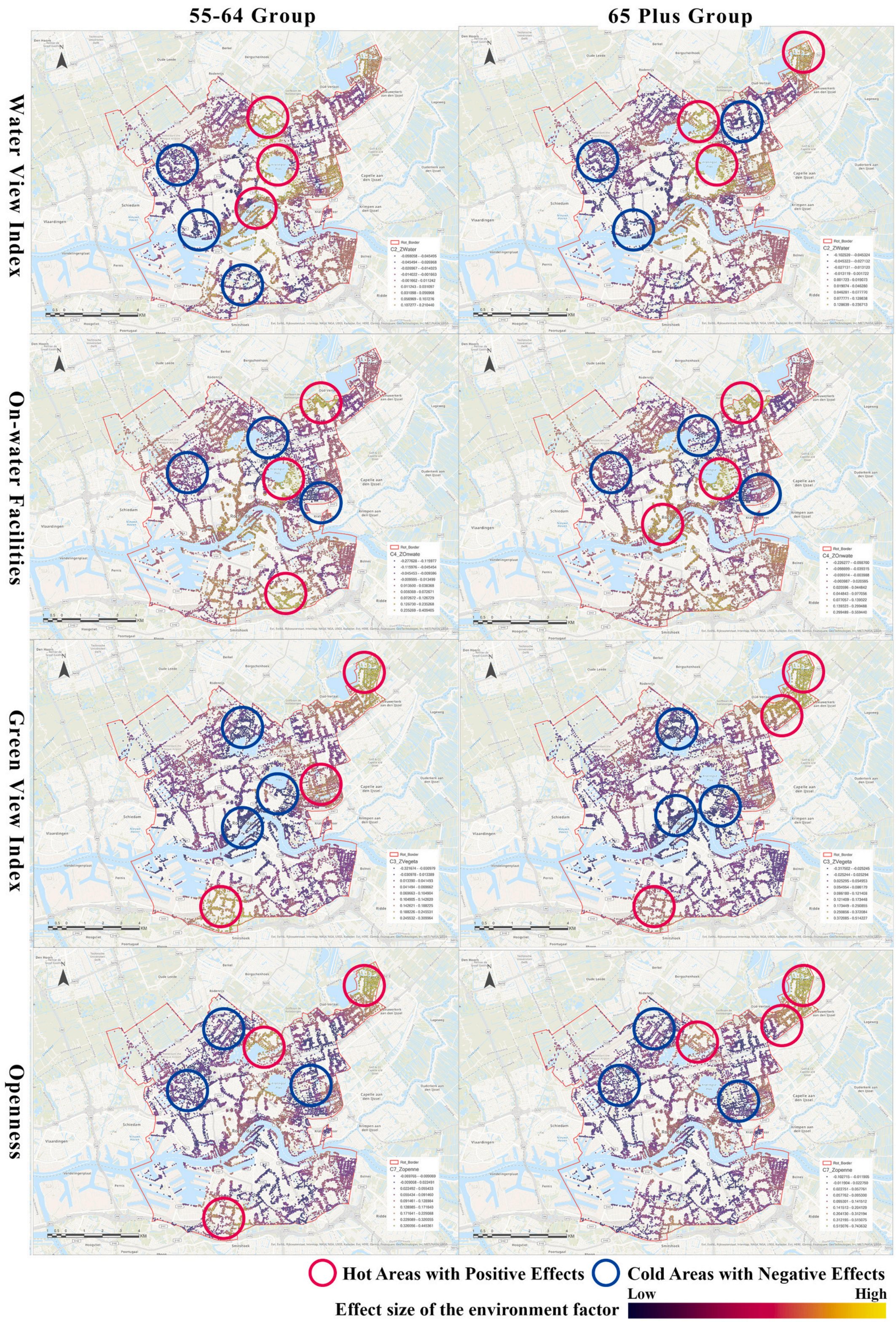

Fig. 4. (*continued*).

and income levels is conducted. The results reveal that despite some similarities between the spatial distribution of recreational running of the elderly group and its population or income distribution patterns, some areas bear fewer older people but present a relatively high intensity and popularity of recreational running activity among the elderly (Fig. 3 [5–6]).

3.2. *GWR results about the role of visual perception in recreational running among different ages*

Fig. 4 presents the significant analysis findings on the local coefficients of visual perception factors at each street segment point in the GWR model. These are categorised and visualised using the Jenks

Natural Breaks method. The results highlight two key dimensions that reflect a significant difference in the impact of water bodies on recreational running in urban areas, including the spatial size and shape of water bodies. Specifically, the positive effects of the WVI are primarily concentrated around large-scale water bodies, while negative effects tend to cluster near minor and linear blue spaces. In contrast, the GWR results for on-water facilities are inconsistent with those for the WVI, as their negative effects also cluster around minor blue spaces, but their effects near large-scale blue spaces are not consistently positive, especially for the fringe areas of large lake blue spaces. Regarding other visual factors, the positive impact of the GVI generally decreases with increasing spatial distance from the city centre, while the areas exhibiting negative effects of openness are mainly clustered around minor or linear blue spaces in the eastern and western parts of Rotterdam.

Furthermore, the GWR analysis results suggest that the influence of visual perception factors on recreational running in urban blue spaces may vary among age groups. The most interesting results relate to the WVI factor, as the waterfront alongside the Maas River presents a clustering area of positive effects for the young group (18–34) but not so significant for the elderly (65plus), with the Nesselande district becoming another attractive area for older people regarding the WVI. Meanwhile, while the spatial patterns of the correlations between on-water facilities in view and recreational running counts remain similar across various age groups, the areas presenting negative effects for the elderly are generally more extensive than those for the younger generation, particularly in the northern part of Rotterdam, such as the Prins Alexander district. Moreover, while the western areas of Rotterdam cluster several areas with positive effects of GVI on running counts for the younger age group (18–34), the effects within these locales could be largely negative for the other three age groups. Comparatively, in the Nesselande district, the positive impacts of GVI on recreational running for middle-aged people and the elderly may change to negative for the younger group (18–34). Similar findings about the differences of sensitive areas across age groups could be found for openness, as reflected in the inconsistent results for the younger population (18–34) and the other age groups surrounding the two lakes in the city centre, the Maas River, and the Nesselande district. The complete GWR model results are presented in the supplementary materials.

3.3. *Correlations between environmental factors and recreational running among different ages*

Table 2 reports the impact of environmental factors on recreational running among different age groups using three regression models. Supplementing the spatial autocorrelation impact revealed in GWR models, the results of adjusted R^2 indicate that the SEM model is better than the SLM and OLS models in explaining the associations between blue space's visual perception and recreational running activity.

In general, the direction of the variables' effects is uniform across various regression models, while the statistical significance and effect sizes show variation. For the visual perception factors of blue space, with spatial effect controlled, negative correlations between WVI and recreational running are observed across all age groups. Consistent with the findings of the different impacts of WVI between young and older people revealed in GWR models, the impacts of WVI are more significant for the young (18–34) and middle (35–54) age groups. In contrast, despite the result of OLS is significant for the 55–64 age group, the results of SLM and SEM show that on-water facilities only present a positive correlation with the recreational running of the elderly group (65plus) and the effect size in SEM is larger than that in SLM. Concerning the other visual perception factors, positive correlations between GVI and recreational running are observed in all models among different age groups. However, the influence of the green view diminishes with age, a phenomenon also evident in the Nesselande district in the GWR models. The openness shows a robust and positive impact on recreational running in all models, particularly for individuals aged between 35 and 54. Similar to the patterns of WVI, building elements in view are negatively associated with recreational running across all demographic groups, with a less pronounced effect in the middle-aged and elderly cohorts compared to the younger generations. The traffic elements negatively affect participants' recreational running in all three models. Notably, the results for on-land facilities show that, with spatial error effect controlled, its general impact on recreational running only remains significant for the 35–54 age groups. Similarly, while the results of OLS models are significant among various age groups, with spatial effects controlled, visual complexity is only positively correlated with the 18–34 age group.

Some significant correlations with recreational running are observed for built environment factors, including general indicators and the existence of specific facilities. Similar to GVI, the choice value of street segments is positively associated with recreational running counts, while the impact progressively weakens with age. Similar patterns are found for the effects of land use mix of blue space's surrounding areas. In contrast, considering the spatial effect, the analysis of street integration value yields inconsistent results, and only the 18–34 age group observes consistent positive effects. Considering public facilities, the number of bus stations is negatively associated with recreational running among all groups, and this correlation intensifies with age. Another factor contributing to people's recreational running activity is the spatial configuration of cultural and sports facilities. The number of sports facilities demonstrates positive associations with recreational running in all groups, with a stronger effect observed in the younger generations. Despite no significant effects reported in OLS models, the number of service facilities is slightly negatively associated with running counts when controlling spatial effects. Interestingly, apart from the choice value of street segments, the results of other built environment factors in SEM are significantly larger than those in SLM.

4. Discussions

Compelling evidence supports the positive influence of the urban natural environment on human health, making it a practical approach to alleviating current urban health issues (Bratman et al., 2019; Hartig et al., 2014; Zhang, Nijhuis, & Newton, 2022). As a result, the physical activity promotion mechanism of urban natural environments is being actively introduced into many urban planning and practices to mitigate the prevalence of physical inactivity and foster a sustainable healthy urban environment for the future (Althoff et al., 2017; Huang, Tian, & Yuan, 2023; Zhang et al., 2024). However, to enhance comprehension of the physical activity promotion mechanisms within natural environments across diverse age populations and to extend these practices to often overlooked blue spaces, empirical studies are still needed to collect detailed evidence, providing more direct and targeted support for proposing refined practical actions (WHO, 2021). Utilising the Rotterdam metropolitan area as a case study, this research integrates multi-source data, such as VGI, SVIs, and POI data, to examine the influence of visual perception and relevant environmental factors of blue spaces on recreational running, particularly emphasising variations among different age groups. The findings in this study can be summarised into the following three major aspects.

4.1. *Spatial distributions and features of recreational running among different ages*

First, this study proves the distinct attractiveness of blue space to the emergence and distribution of recreational running in urban environments. According to the mapping analysis, the northern bank of the Nieuwe Maas River has become a heated locale for recreational running, echoing the literature about the riverfront as an appealing place for physical activities (Boakye et al., 2021; Gascon et al., 2017; Vert et al., 2019; Völker & Kistemann, 2015). Meanwhile, although the uneven distribution of population could partly interpret it, the centre areas perform better than peri-urban areas in terms of the intensity of

Table 2
The regression results for recreational running among different age groups.

Regression model results (recreational running)	18–34 (S. Coef.)			35–54 (S. Coef.)			55–64 (S. Coef.)			65Plus (S. Coef.)		
	OLS	SLM	SEM	OLS	SLM	SEM	OLS	SLM	SEM	OLS	SLM	SEM
Visual Perception Factors												
Water View Index	−0.021	−0.022*	−0.046**	−0.050**	−0.033**	−0.047**	−0.036**	−0.024*	−0.033**	−0.035**	−0.026**	−0.035**
On water facilities	0.018	−0.006	−0.004	0.012	−0.002	0.002	0.024*	0.007	0.010	0.027**	0.016*	0.021*
Green View Index	0.114**	0.099**	0.171**	0.141**	0.112**	0.167**	0.133**	0.105**	0.157**	0.117**	0.084**	0.116**
Openness	0.055**	0.031*	0.033*	0.067**	0.044**	0.037**	0.051**	0.039**	0.038**	0.038**	0.029**	0.029**
Building elements	−0.595**	−0.239**	−0.314**	−0.364**	−0.158**	−0.180**	−0.183**	−0.075**	−0.098**	−0.136**	−0.062**	−0.092**
On land facilities	−0.064**	−0.022*	−0.012	−0.084**	−0.037**	−0.020*	−0.063**	−0.026**	−0.014	−0.055**	−0.024**	−0.014
Traffic elements	−0.104**	−0.072**	−0.087**	−0.108**	−0.077**	−0.089**	−0.099**	−0.070**	−0.080**	−0.082**	−0.059**	−0.068**
Visual complexity	0.070**	0.040**	0.005	0.041*	0.021	−0.014	0.026	0.013	−0.018	0.026*	0.0.019	0.000
Built Environment Factors												
Choice Value	0.706**	0.678**	0.678**	0.737**	0.694**	0.691**	0.606**	0.570**	0.571**	0.460**	0.425**	0.428**
Integration Value	0.256**	0.074**	0.360**	0.043*	−0.012	0.254**	0.010	−0.026*	0.166**	−0.079**	−0.059**	0.071**
Land Use Mix	0.376**	0.171**	0.311**	0.353**	0.175**	0.297**	0.308**	0.151**	0.272**	0.207**	0.100**	0.186**
Bus Stations	−0.023	−0.029*	−0.088**	−0.044**	−0.039**	−0.102**	−0.118**	−0.068**	−0.144**	−0.127**	−0.066**	−0.140**
Tram Stations	0.122**	0.033*	0.093*	−0.007	−0.018	−0.041	−0.005	−0.015	−0.048	−0.009	−0.015	−0.047*
Sport Facilities	0.237**	0.123**	0.324**	0.197**	0.113**	0.258**	0.195**	0.105**	0.240**	0.146**	0.077**	0.183**
Cultural Areas	0.160**	0.084**	0.219**	0.164**	0.091**	0.192**	0.115**	0.062**	0.125**	0.110**	0.056**	0.115**
Restaurant & Cafe	−0.021	−0.004	−0.079	−0.024	−0.015	−0.042	0.066**	0.037*	0.024	0.023	0.014	−0.021
Service Facilities	−0.064**	−0.028*	−0.031	−0.067**	−0.032**	−0.058**	0.036**	−0.017	−0.052*	−0.015	−0.007	−0.029
Contextual Variables												
Urbanicity	0.026	0.036*	−0.007	0.033*	0.040**	0.049	−0.116**	−0.039**	−0.067*	−0.161**	−0.063**	−0.104**
Non-western Population	−0.156**	−0.052**	−0.103**	−0.089**	−0.030*	−0.027	−0.064**	−0.022	0.020	−0.037**	−0.011	0.004
Low-income Population	−0.030	−0.016	−0.049	−0.125**	−0.061**	−0.124**	−0.169**	−0.077**	−0.136**	−0.184**	−0.084**	−0.156**
(Intercept)	3.823**	1.597**	3.848**	3.984**	1.851**	4.009**	2.447**	1.097**	2.478**	1.578**	0.703**	1.600**
LAMBDA			0.688**			0.667**			0.644**			0.621**
Adj. R2	0.411	0.567	0.599	0.342	0.488	0.532	0.284	0.439	0.471	0.219	0.377	0.399

recreational running across all age groups, perhaps owing to the better-organised urban environments and facilities. Furthermore, some popular areas and streets for running are identified in our analysis, i.e., the streets along the Maas River and the Kralingen Lake, which perform a consistent attractiveness to all age groups across the city. The identification of hotspots for recreational running aligns with contemporary observations and cross-sectional studies, indicating that the large-scale blue spaces, particularly those with symbolic values, exhibit greater allure for land-based light-intensity physical activities compared to smaller counterparts (Pasanen et al., 2019; Völker & Kistemann, 2013, 2015).

Importantly, mapping results illustrate the characteristics and differences in preferences for recreational running locations across age groups. While some studies suggest that different age groups may favour various running locations (Dean et al., 2020; Grow et al., 2008; Wang et al., 2016), the mapping results provide more detailed evidence and understanding. On the one hand, in the vicinity of blue spaces, the spatial distributions of recreational running become more concentrated with increasing age. The possible explanations could be attributed to three aspects. Firstly, individuals may develop an increasing familiarity and place attachment with specific locations throughout their lives. Second, social interactions tend to become more fixed and concentrated with age, particularly among specific acquaintances such as neighbours, potentially contributing to a narrowing range of recreational running. Third, age-related declines in mobility could further contribute to shaping usage patterns for running by the elderly.

On the other hand, compared to other age groups, the elderly are more willing to run in blue spaces outside the city centre, especially in neighbourhoods situated in the north and northeast of Rotterdam. This may be attributed to the inherent spatial distribution and greater income flexibility among the elderly, who may seek to enjoy life in quieter environments away from the crowded city centre. The mapping results could provide valuable insights that contribute to formulating urban visions at the city/regional scale, such as improvements in the provision and maintenance of blue spaces in city fringes to alleviate disparities in running opportunities.

4.2. The attractiveness of multi-faceted factors for recreational running of different age groups

This study reveals the correlations between environmental factors of blue spaces and recreational running behaviour among various age groups, considering spatial heterogeneity and age-specific variations. The GWR analysis indicates that the impacts of visual perception factors on recreational running may vary based on the spatial size and shape of water bodies. The study's key empirical finding is that despite the positive impact of the WVI on recreational running around large-scale water bodies, this effect may turn negative in the context of small-scale and linear blue spaces. In contrast, the impact of on-water facilities is more mixed and tends to be negative at the fringe areas of large lakes. The study also provides novel evidence regarding the differences across age groups. Specifically, the effects of WVI may vary for young adults (18–34) and the elderly (65plus), particularly in the blue spaces alongside the Nieuwe Maas River and Nesselande district. Furthermore, the role of on-water facilities may be more dominant for older people's running preferences.

The spatial regression results of visual perception further examine differences in environmental preferences for recreational running among different age groups. The WVI is negatively associated with recreational running intensity for all age groups, with diminishing effects as age increases. This interesting finding, inconsistent with prior studies, may be attributed, in part, to variations in water types (Garrett et al., 2019; Nutsford et al., 2016). Specifically, large-scale blue spaces positively influence running behaviour, while small-scale blue spaces have the opposite effect, as suggested by the results of the GWR model. Safety concerns associated with water bodies, particularly for the elderly, may also contribute to these findings (White et al., 2020). Furthermore, consistent with various existing studies on general urban environments (Boakye et al., 2021; Huang et al., 2022; Schuurman et al., 2021; Zhang, Song, & Zhang, 2022), eye-level greenness has a positive effect on recreational running across all age groups. However, the influence decreases with age, which may be attributed to older individuals' relatively stronger demand for actual health benefits in running activities within blue spaces (e.g., comfortability, sociality, and safety) that, to some extent, diminishes their emphasis on the visual experience of greenery (Levy-Storms et al., 2018; Sugiyama & Ward Thompson, 2007). Similarly, buildings and traffic elements in view exhibit a negative correlation with recreational running across all age groups. This is in line with findings from the existing studies (Huang, Tian, & Yuan, 2023; Jiang et al., 2022; Zhang, Song, & Zhang, 2022), while a diminishing correlation effect is observed with increasing age. The potential explanation may be rooted in older individuals' greater flexibility and adaptability to public spaces compared to younger and middle-aged groups (Puhakka et al., 2015). Moreover, the visual complexity of blue spaces only indicates a significant positive association with recreational running among the young generation (18–34). This finding is supported by research on public curiosity and attention, which suggests that young people are more easily stimulated by curiosity and more susceptible to visual attractions in urban settings (Camp et al., 1984; Tapiro et al., 2020). Blue spaces with relatively higher visual complexity may stimulate young people's curiosity and desire to explore, influencing their environmental preferences for recreational running. However, higher visual complexity is often associated with lower safety perception, which may deter older individuals from selecting such areas for running (Ottoni et al., 2021).

The spatial correlation results of built environment factors suggest the differences in functional preferences of different age groups in recreational running. A well-organised road network and a high land use mix positively influence recreational running, aligning with previous studies highlighting their role in facilitating comfortable running experiences (Dang et al., 2023; Huang, Tian, & Yuan, 2023; Yang, Yu, et al., 2022). Interestingly, younger individuals prioritise these factors more and are attracted to blue spaces with well-organised street networks. This is perhaps due to the differences in the physical ability and the total length of recreational running across various age groups, which further lead to differences in route selection. Younger individuals with better physical fitness plan longer running routes, emphasising the significant influence of street accessibility (e.g., streets with higher choice or integration value) on their route preferences (Burton et al., 2012). Some notable differences are observed in the impact of diverse facilities on recreational running across age groups. The presence of bus stops around blue spaces exhibits a negative correlation with running activity, particularly among older individuals. This may be attributed to the fact that bus stops in Rotterdam are often positioned along streets, interfering with running routes within linear blue spaces. This interference may influence route choices, particularly considering older individuals' greater emphasis on safety within running environments (Ottoni et al., 2021). In contrast, younger individuals prefer blue spaces adjacent to various sports facilities and cultural areas for recreational running, potentially stemming from the younger demographic's greater inclination to combine running with other recreational activities (Yang, Zhang, et al., 2022). However, the associations between restaurants and cafes and running activity are not statistically significant across all age groups. This observation may be attributed to individuals' tendency to visit these places during less strenuous activities, such as walking, as running entails distinct patterns of behaviour (Kim, 2015).

4.3. Implications for planning and design

The results of this analysis support evidence-based policy-making and spatial interventions that promote recreational running and contribute to the development of healthy cities, aligning with the human-centered urban design paradigm and echoing nature-based solutions (Fang et al., 2024; Gehl, 2013; Jacobs, 1961; Lafortezza et al., 2018; Wang, 2023). First, in spatial interventions for designing running-friendly blue spaces, emphasis on visual perception and related environmental factors is crucial, moving beyond macro city visions (e.g., provision of blue space at land use level). For instance, practitioners should enhance the diversity of greenery and decrease the exposure of building and traffic-related elements at eye level when designing blue spaces, particularly those intended to promote recreational physical activities. Secondly, given the highlighted disparities among various age groups in this study, spatial interventions should comprehensively account for the specific environmental preferences of different age groups regarding recreational running, with particular attention to vulnerable groups like the elderly. For example, incorporating diverse vegetation, landscape elements, and integrating blue spaces with cultural and sports facilities could evoke enthusiasm for running among young individuals. In contrast, for older people, factors such as convenience and safety perception in blue spaces exert a more pronounced impact on their inclination to run. Third, practitioners should implement tailored strategies for diverse blue spaces to promote running activity. Ensuring water visibility in large-scale blue spaces could foster running, providing positive psychological effects as well. Conversely, in small-scale blue spaces, a combination of vegetation and facilities should be employed to create a vibrant atmosphere, enticing individuals to run. Fourth, building on spatial heterogeneity analysis, future policy formulation should account for neighbourhood-specific differences to promote equitable running opportunities. Recommendations for planners and policymakers include a focus on enhancing the environmental quality of blue spaces in economically affluent neighbourhoods to maximise the overall health benefits. Simultaneously, attention should be given to blue spaces in deprived neighbourhoods, recognising the potential for health contributions to drive socio-spatial (re)development, especially in attracting residents who prioritise individual health.

On the other hand, some specific strategies and patterns for planning and designing running-friendly blue space highlight the potential of evidence translation and aim to enhance the practicability of research results. Fig. 5 illustrates various planning strategies at the city/community level, encompassing (1) the optimisation of road networks and promotion of mixed land use patterns, (2) enhancement of the spatial layout of public transport facilities or running routes, and (3) integration of cultural and sports facilities with blue spaces. Additionally, Fig. 6 delineates several design patterns at the individual level for running-friendly blue spaces according to the research outcomes, accompanied by detailed diagrams to augment practical potential. Specifically, it recommends (1) increasing eye-level greenery and visual complexity in blue spaces, using a multi-layered configuration of vegetation, while emphasising regular vegetation planting in blue spaces frequently used by the elderly to reduce unsafe perception (Fig. 6 [a]); (2) limiting the proportion of building elements in blue spaces through various forms of vegetation, including street trees and vertical greening (Fig. 6 [b]); (3)

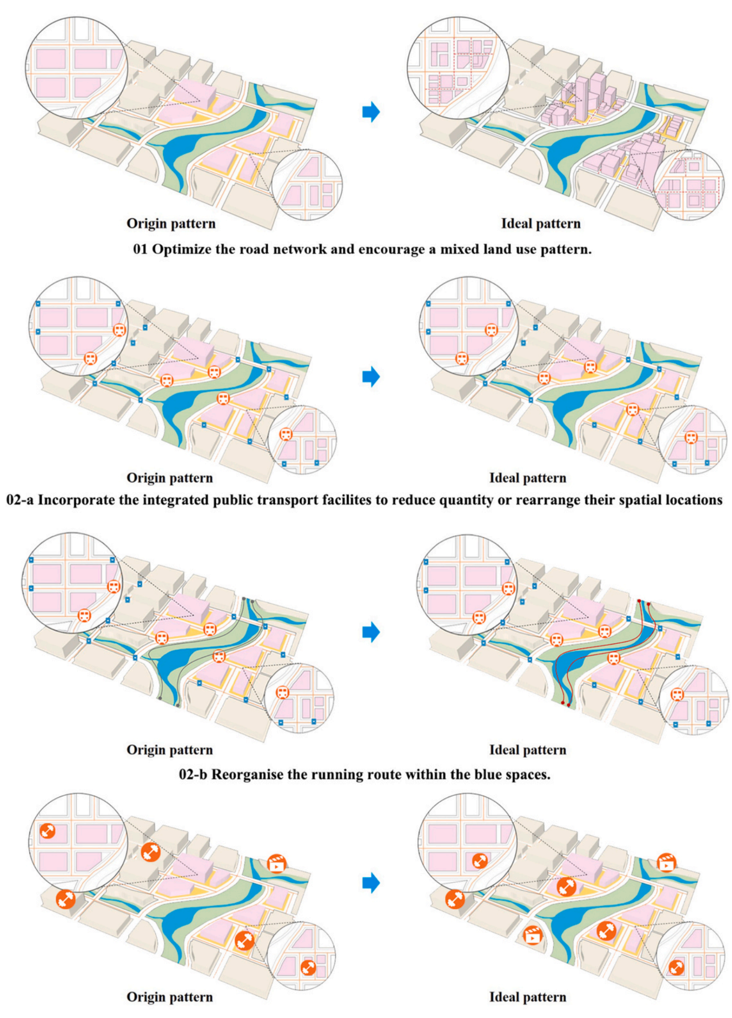

Fig. 5. The spatial planning strategies for running-friendly blue space. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

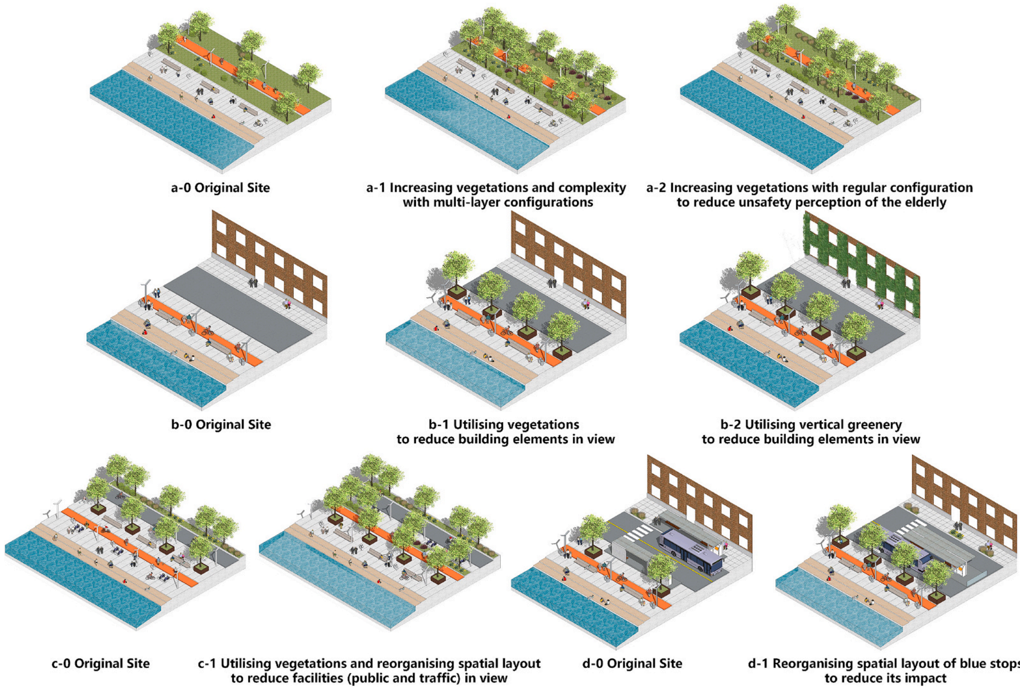

Fig. 6. Detailed spatial patterns for designing running-friendly blue space. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

optimising the spatial arrangement of public facilities to minimise interference with running activities, such as on-land facilities, bus stops, and other traffic-related elements (Fig. 6 [c-d]).

4.4. Strengths and limitations

Aligning with the emphasis on detailed evidence collection in blue-health research and urgent demands to translate research outcomes into spatial interventions (WHO, 2021; Zhang, Nijhuis, & Newton, 2022), this study is novel in its concentration on blue space and examines the impact of both visual perception and built environment factors on the level of recreational running across diverse age groups in highly urbanised areas, with neighbourhood socio-economic contexts controlled. Particularly, the combination of city-level VGI, SVI, and POI data enables distinguishing the differences in environmental and functional preferences for recreational running across various age groups, thus providing nuanced findings and insights for tailoring blue space spatial planning and design to cater for the specific needs of diverse age cohorts. Recognising the potential spatial effects in the distribution of running records, the study employs various models, including GWR, SEM, and SLM, to control and examine this effect comprehensively. Furthermore, this study offers evidence-based planning and design strategies, distinguishing itself from other empirical research endeavours.

Some limitations of this study should be noted, particularly regarding data availability and potential methods. First, despite the individual-scale measurements in VGI data, desensitisation limits the ability to precisely identify the spatial distribution and intensity of recreational running, as the study can only identify the distribution and intensity of running exercise based on the street network. Given the high dependence on the street network for recreational running, it should be acceptable. Second, due to registration and usage regulations of the VGI platform, certain personal data and running data related to specific age groups, such as running data under 18, educational background, gender, and other socio-economic characteristics, cannot be provided. This emphasises the necessity for conducting further qualitative research since supplementary evidence from interviews and observational studies can offer additional insights into the running behaviour of adolescents and children. Third, in light of spatial effects, this research adopts GWR and two spatial regression models, potentially limiting the exploration of other advanced statistical methods, such as Poisson regression or negative binomial regression models suitable for analysing count data and emerging machine learning models considering non-linear relationships. Last, as the current study pays attention to one typical city, worldwide studies are essential to investigate and elucidate the mechanisms of environmental factors influencing recreational running, allowing for a more comprehensive understanding and inference of causality. Moreover, the practical strategies and patterns proposed by this research are applicable to urban environments that are abundant in water resources and share a similar background to Rotterdam. As the research scope broadens and incorporates more factors, some general spatial strategies suitable for cities of diverse backgrounds will be identified and globally advocated, contributing to mitigating the burden caused by health issues and the construction of 'Healthy Cities'.

5. Conclusions

Utilising multi-sourced data (i.e. VGI, SVI, POI data) and the advanced machine learning approach, this study aims to examine whether and how the visual perception and related environmental factors of blue space could influence the recreational running in Rotterdam, with a particular focus on distinguishing the divergent environmental preferences across various age groups. The findings in our study prove the significant role of visual perception factors of blue spaces in the correlations to recreational running, which might vary depending on different indicators and age groups. Particularly, some key findings are located between the young (18–34) and the elderly (65plus): WVI exhibited a positive impact on the young's running around the Nieuwe Maas River, the negative effects of on-water facilities on the elderly were spatially widespread, GVI positively influenced the young adults' running in western Rotterdam, and the visual openness around large water bodies had a positive impact on running of youngs while exerting the opposite effect on the elderly. Concurrently, considering spatial effects, this study investigates the interplay between built environment factors and the extent of recreational running. Specifically, positive correlations were identified between GVI, openness, choice, integration, land use mix, and the number of sports and cultural facilities across all age groups. In contrast, WVI, building elements, traffic elements, on-land facilities, and bus stop quantity exhibited negative correlations with running across all ages. The effects were found to vary with age, with the impact of several factors decreasing as age increased. These findings collectively enhance and deepen the nuanced comprehension of the existing knowledge on the correlation between blue space and physical activity, emphasising age-related distinctions in visual perception and functional preferences. On the other hand, relying on these results, this paper proposes specific strategies and principles for the spatial planning and design of blue spaces. By translating the evidence into strategies and designs directly applicable to creating health-promoting and running-friendly blue spaces, this study offers practical support for future practitioners aiming to advance healthy cities and implement nature-based solutions.

CRediT authorship contribution statement

Haoxiang Zhang: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Steffen Nijhuis:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Investigation, Conceptualization. **Caroline Newton:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Investigation, Conceptualization. **Lu Shan:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization.

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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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cities.2025.105917.

Data availability

Data will be made available on request.

References

Althoff, T., Sosič, R., Hicks, J. L., King, A. C., Delp, S. L., & Leskovec, J. (2017). Large-scale physical activity data reveal worldwide activity inequality. *Nature, 547*(7663), 336–339. https://doi.org/10.1038/nature23018

de Bell, S., Graham, H., Jarvis, S., & White, P. (2017). The importance of nature in mediating social and psychological benefits associated with visits to freshwater blue space. *Landscape and Urban Planning, 167*(May), 118–127. https://doi.org/10.1016/j.landurbplan.2017.06.003

Biljecki, F., & Ito, K. (2021). Street view imagery in urban analytics and GIS: A review. *Landscape and Urban Planning, 215*(July), Article 104217. https://doi.org/10.1016/j.landurbplan.2021.104217

Boakye, K. A., Amram, O., Schuna, J. M., Duncan, G. E., & Hystad, P. (2021). GPS-based built environment measures associated with adult physical activity. *Health & Place, 70*(June), Article 102602. https://doi.org/10.1016/j.healthplace.2021.102602

Bratman, G. N., Anderson, C. B., Berman, M. G., Cochran, B., de Vries, S., Flanders, J., … Daily, G. C. (2019). Nature and mental health: An ecosystem service perspective. *Science Advances, 5*(7). https://doi.org/10.1126/sciadv.aax0903

Bratman, G. N., Daily, G. C., Levy, B. J., & Gross, J. J. (2015). The benefits of nature experience: Improved affect and cognition. *Landscape and Urban Planning, 138*, 41–50. https://doi.org/10.1016/j.landurbplan.2015.02.005

Brown, R. D., & Corry, R. C. (2011). Evidence-based landscape architecture: The maturing of a profession. *Landscape and Urban Planning, 100*(4), 327–329. https://doi.org/10.1016/j.landurbplan.2011.01.017

Burton, N. W., Khan, A., & Brown, W. J. (2012). How, where and with whom? Physical activity context preferences of three adult groups at risk of inactivity. *British Journal of Sports Medicine, 46*(16), 1125–1131. https://doi.org/10.1136/bjsports-2011-090554

Camp, C. J., Rodrigue, J. R., & Olson, K. R. (1984). Curiosity in young, middle-aged, and older adults. *Educational Gerontology, 10*(5), 387–400. https://doi.org/10.1080/0380127840100504

CBS. (2023). Bestand bodemgebruik. https://www.cbs.nl/nl-nl/dossier/nederland-regionaal/geografische-data/bestand-bodemgebruik.

Dang, Y., Zhan, D., Qiu, L., Wu, S., & Cui, Y. (2023). Effects of the built environment on residents' subjective well-being and behaviours: A case of Hangzhou, China. *Journal of Housing and the Built Environment, 38*(1), 497–514. https://doi.org/10.1007/s10901-022-09955-z

Dean, J., Biglieri, S., Drescher, M., Garnett, A., Glover, T., & Casello, J. (2020). Thinking relationally about built environments and walkability: A study of adult walking behavior in Waterloo, Ontario. *Health & Place, 64*(April), Article 102352. https://doi.org/10.1016/j.healthplace.2020.102352

Dong, L., Jiang, H., Li, W., Qiu, B., Wang, H., & Qiu, W. (2023). Assessing impacts of objective features and subjective perceptions of street environment on running amount: A case study of Boston. *Landscape and Urban Planning, 235*(March), Article 104756. https://doi.org/10.1016/j.landurbplan.2023.104756

Duhl, L. J., & Sanchez, A. K. (1999). *Healthy cities and the city planning process*. World Health Organization Regional Office for Europe.

Fang, X., Li, J., Ma, Q., Zhou, R., & Du, S. (2024). A quantitative review of nature-based solutions for urban sustainability (2016–2022): From science to implementation. *Science of the Total Environment, 927*(April), Article 172219. https://doi.org/10.1016/j.scitotenv.2024.172219

Frantzeskaki, N., & Tilie, N. (2014). The dynamics of urban ecosystem governance in Rotterdam, The Netherlands. *AMBIO, 43*(4), 542–555. https://doi.org/10.1007/s13280-014-0512-0

Garrett, J. K., White, M. P., Huang, J., Ng, S., Hui, Z., Leung, C., … Wong, M. C. S. (2019). Urban blue space and health and wellbeing in Hong Kong: Results from a survey of older adults. *Health & Place, 55*(November 2018), 100–110. https://doi.org/10.1016/j.healthplace.2018.11.003

Gascon, M., Zijlema, W., Vert, C., White, M. P., & Nieuwenhuijsen, M. J. (2017). Outdoor blue spaces, human health and well-being: A systematic review of quantitative studies. *International Journal of Hygiene and Environmental Health, 220*(8), 1207–1221. https://doi.org/10.1016/j.ijheh.2017.08.004

Gehl, J. (2013). *Cities for people (issue 1)*. Island press.

Gidlow, C. J., Jones, M. V., Hurst, G., Masterson, D., Clark-Carter, D., Tarvainen, M. P., … Nieuwenhuijsen, M. (2016). Where to put your best foot forward: Psycho-physiological responses to walking in natural and urban environments. *Journal of Environmental Psychology, 45*, 22–29. https://doi.org/10.1016/j.jenvp.2015.11.003

Grellier, J., White, M. P., Albin, M., Bell, S., Elliott, L. R., Gascón, M., … Fleming, L. E. (2017). BlueHealth: A study programme protocol for mapping and quantifying the potential benefits to public health and well-being from Europe's blue spaces. *BMJ Open, 7*(6), 1–10. https://doi.org/10.1136/bmjopen-2017-016188

Grow, H. M., Saelens, B. E., Kerr, J., Durant, N. H., Norman, G. J., & Sallis, J. F. (2008). Where are youth active? Roles of proximity, active transport, and built environment. *Medicine & Science in Sports & Exercise, 40*(12), 2071–2079. https://doi.org/10.1249/MSS.0b013e3181817baa

Harpham, T. (2009). Urban health in developing countries: What do we know and where do we go? *Health & Place, 15*(1), 107–116. https://doi.org/10.1016/j.healthplace.2008.03.004

Hartig, T., & Kahn, P. H. (2016). Living in cities, naturally. *Science, 352*(6288), 938–940. https://doi.org/10.1126/science.aaf3759

Hartig, T., Mitchell, R., De Vries, S., & Frumkin, H. (2014). Nature and health. *Annual Review of Public Health, 35*, 207–228. https://doi.org/10.1146/annurev-publhealth-032013-182443

Heaviside, C., Macintyre, H., & Vardoulakis, S. (2017). The urban heat island: Implications for health in a changing environment. *Current Environmental Health Reports, 4*(3), 296–305. https://doi.org/10.1007/s40572-017-0150-3

Helbich, M., Yao, Y., Liu, Y., Zhang, J., Liu, P., & 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*(January), 107–117. https://doi.org/10.1016/j.envint.2019.02.013

Huang, D., Jiang, B., & Yuan, L. (2022). Analysing the effects of nature exposure on perceived satisfaction with running routes: An activity path-based measure approach. *Urban Forestry & Urban Greening, 68*(October 2021), Article 127480. https://doi.org/10.1016/j.ufug.2022.127480

Huang, D., Kyttä, M., Kajosaari, A., Xie, X., & Zhang, J. (2023). One approach does not fit all settings: Exploring the effects of natural and built environments on running pleasantness across places. *Building and Environment, 245*(July). https://doi.org/10.1016/j.buildenv.2023.110961

Huang, D., Tian, M., & Yuan, L. (2023). Sustainable design of running friendly streets: Environmental exposures predict runnability by Volunteered Geographic

Information and multilevel model approaches. *Sustainable Cities and Society, 89*, Article 104336. https://doi.org/10.1016/j.scs.2022.104336

Hunter, R. F., Nieuwenhuijsen, M., Fabian, C., Murphy, N., O'Hara, K., Rappe, E., … Kahlmeier, S. (2023). Advancing urban green and blue space contributions to public health. *The Lancet Public Health, 8*(9), e735–e742. https://doi.org/10.1016/S2468-2667(23)00156-1

Jacobs, J. (1961). *The death and life of great American cities*. Random House.

Jiang, H., Dong, L., & Qiu, B. (2022). How are macro-scale and micro-scale built environments associated with running activity? The application of Strava data and deep learning in inner London. *ISPRS International Journal of Geo-Information, 11* (10), 504. https://doi.org/10.3390/ijgi11100504

Kang, Y., Zhang, F., Gao, S., Lin, H., & Liu, Y. (2020). A review of urban physical environment sensing using street view imagery in public health studies. *Annals of GIS, 26*(3), 261–275. https://doi.org/10.1080/19475683.2020.1791954

Kim, H. (2015). Walking distance, route choice, and activities while walking: A record of following pedestrians from transit stations in the San Francisco Bay area. *Urban Design International, 20*(2), 144–157. https://doi.org/10.1057/udi.2015.2

Laddu, D., Paluch, A. E., & LaMonte, M. J. (2021). The role of the built environment in promoting movement and physical activity across the lifespan: Implications for public health. *Progress in Cardiovascular Diseases, 64*, 33–40. https://doi.org/10.1016/j.pcad.2020.12.009

Lafortezza, R., Chen, J., van den Bosch, C. K., & Randrup, T. B. (2018). Nature-based solutions for resilient landscapes and cities. *Environmental Research, 165*(December 2017), 431–441. https://doi.org/10.1016/j.envres.2017.11.038

Levy-Storms, L., Chen, L., & Loukaitou-Sideris, A. (2018). Older adults' needs and preferences for open space and physical activity in and near parks: A systematic review. *Journal of Aging and Physical Activity, 26*(4), 682–696. https://doi.org/10.1123/japa.2016-0354

Liu, J., Ettema, D., & Helbich, M. (2023). Street view environments are associated with the walking duration of pedestrians: The case of Amsterdam, the Netherlands. *Landscape and Urban Planning, 235*(March), Article 104752. https://doi.org/10.1016/j.landurbplan.2023.104752

Lu, Y., Yang, Y., Sun, G., & Gou, Z. (2019). Associations between overhead-view and eye-level urban greenness and cycling behaviors. *Cities, 88*(May 2018), 10–18. https://doi.org/10.1016/j.cities.2019.01.003

Ma, B., Hauer, R. J., Xu, C., & Li, W. (2021). Visualising evaluation model of human perceptions and characteristic indicators of landscape visual quality in urban green spaces by using nomograms. *Urban Forestry & Urban Greening, 65*(August), Article 127314. https://doi.org/10.1016/j.ufug.2021.127314

MacKerron, G., & Mourato, S. (2013). Happiness is greater in natural environments. *Global Environmental Change, 23*(5), 992–1000. https://doi.org/10.1016/j.gloenvcha.2013.03.010

Maroko, A. R., Maantay, J. A., Sohler, N. L., Grady, K. L., & Arno, P. S. (2009). The complexities of measuring access to parks and physical activity sites in New York City: A quantitative and qualitative approach. *International Journal of Health Geographics, 8*(1), 34. https://doi.org/10.1186/1476-072X-8-34

McDougall, C. W., Hanley, N., Quilliam, R. S., & Oliver, D. M. (2022). Blue space exposure, health and well-being: Does freshwater type matter? *Landscape and Urban Planning, 224*, Article 104446. https://doi.org/10.1016/j.landurbplan.2022.104446

McDougall, C. W., Quilliam, R. S., Hanley, N., & Oliver, D. M. (2020). Freshwater blue space and population health: An emerging research agenda. *Science of the Total Environment, 737*, Article 140196. https://doi.org/10.1016/j.scitotenv.2020.140196

Nutsford, D., Pearson, A. L., Kingham, S., & Reitsma, F. (2016). Residential exposure to visible blue space (but not green space) associated with lower psychological distress in a capital city. *Health & Place, 39*, 70–78. https://doi.org/10.1016/j.healthplace.2016.03.002

Ottoni, C. A., Sims-Gould, J., & Winters, M. (2021). Safety perceptions of older adults on an urban greenway: Interplay of the social and built environment. *Health & Place, 70*, Article 102605. https://doi.org/10.1016/j.healthplace.2021.102605

Pasanen, T. P., White, M. P., Wheeler, B. W., Garrett, J. K., & Elliott, L. R. (2019). Neighbourhood blue space, health and wellbeing: The mediating role of different types of physical activity. *Environment International, 131*, Article 105016. https://doi.org/10.1016/j.envint.2019.105016

Perchoux, C., Kestens, Y., Brondeel, R., & Chaix, B. (2015). Accounting for the daily locations visited in the study of the built environment correlates of recreational walking (the RECORD Cohort Study). *Preventive Medicine, 81*, 142–149. https://doi.org/10.1016/j.ypmed.2015.08.010

Peters, K., Elands, B., & Buijs, A. (2010). Social interactions in urban parks: Stimulating social cohesion? *Urban Forestry & Urban Greening, 9*(2), 93–100. https://doi.org/10.1016/j.ufug.2009.11.003

Puhakka, R., Poikolainen, J., & Karisto, A. (2015). Spatial practises and preferences of older and younger people: Findings from the Finnish studies. *Journal of Social Work Practice, 29*(1), 69–83. https://doi.org/10.1080/02650533.2014.993948

Rasidi, M. H., Jamirsah, N., & Said, I. (2012). Urban green space design affects urban residents' social interaction. *Procedia - Social and Behavioral Sciences, 68*(November), 464–480. https://doi.org/10.1016/j.sbspro.2012.12.242

Remme, R. P., Frumkin, H., Guerry, A. D., King, A. C., Mandle, L., Sarabu, C., … Daily, G. C. (2021). An ecosystem service perspective on urban nature, physical activity, and health. *Proceedings of the National Academy of Sciences of the United States of America, 118*(22), 1–10. https://doi.org/10.1073/PNAS.2018472118

Rydin, Y., Bleahu, A., Davies, M., Dávila, J. D., Friel, S., De Grandis, G., … Wilson, J. (2012). Shaping cities for health: Complexity and the planning of urban environments in the 21st century. *The Lancet, 379*(9831), 2079–2108. https://doi.org/10.1016/S0140-6736(12)60435-8

Salgado, M., Madureira, J., Mendes, A. S., Torres, A., Teixeira, J. P., & Oliveira, M. D. (2020). Environmental determinants of population health in urban settings. A systematic review. *BMC Public Health, 20*(1), 853. https://doi.org/10.1186/s12889-020-08905-0

Sallis, J. F., Cerin, E., Conway, T. L., Adams, M. A., Frank, L. D., Pratt, M., … Owen, N. (2016). Physical activity in relation to urban environments in 14 cities worldwide: A cross-sectional study. *The Lancet, 387*(10034), 2207–2217. https://doi.org/10.1016/S0140-6736(15)01284-2

Schuurman, N., Rosenkrantz, L., & Lear, S. A. (2021). Environmental preferences and concerns of recreational road runners. *International Journal of Environmental Research and Public Health, 18*(12), 6268. https://doi.org/10.3390/ijerph18126268

Sicard, P., Agathokleous, E., Anenberg, S. C., De Marco, A., Paoletti, E., & Calatayud, V. (2023). Trends in urban air pollution over the last two decades: A global perspective. *Science of the Total Environment, 858*(July 2022), Article 160064. https://doi.org/10.1016/j.scitotenv.2022.160064

Stansfeld, S., Haines, M., & Brown, B. (2000). Noise and health in the urban environment. *Reviews on Environmental Health, 15*(1–2). https://doi.org/10.1515/REVEH.2000.15.1-2.43

Sugiyama, T., & Ward Thompson, C. (2007). Older people's health, outdoor activity and supportiveness of neighbourhood environments. *Landscape and Urban Planning, 83* (2–3), 168–175. https://doi.org/10.1016/j.landurbplan.2007.04.002

Tapiro, H., Oron-Gilad, T., & Parmet, Y. (2020). Pedestrian distraction: The effects of road environment complexity and age on pedestrian's visual attention and crossing behavior. *Journal of Safety Research, 72*, 101–109. https://doi.org/10.1016/j.jsr.2019.12.003

Tian, D., Wang, J., Xia, C., Zhang, J., Zhou, J., Tian, Z., Zhao, J., Li, B., & Zhou, C. (2024). The relationship between green space accessibility by multiple travel modes and housing prices: A case study of Beijing. *Cities, 145*(January 2023), Article 104694. https://doi.org/10.1016/j.cities.2023.104694

Triguero-Mas, M., Dadvand, P., Cirach, M., Martínez, D., Medina, A., Mompart, A., … Nieuwenhuijsen, M. J. (2015). Natural outdoor environments and mental and physical health: Relationships and mechanisms. *Environment International, 77*, 35–41. https://doi.org/10.1016/j.envint.2015.01.012

Troy, A., Nunery, A., & Grove, J. M. (2016). The relationship between residential yard management and neighborhood crime: An analysis from Baltimore City and county. *Landscape and Urban Planning, 147*, 78–87. https://doi.org/10.1016/j.landurbplan.2015.11.004

UN General Assembly. (2015). *Transforming our world: The 2030 agenda for sustainable development*. United Nations.

Vert, C., Carrasco-Turigas, G., Zijlema, W., Espinosa, A., Cano-Riu, L., Elliott, L. R., … Gascon, M. (2019). Impact of a riverside accessibility intervention on use, physical activity, and wellbeing: A mixed methods pre-post evaluation. *Landscape and Urban Planning, 190*(July), Article 103611. https://doi.org/10.1016/j.landurbplan.2019.103611

Vink, R., & Varró, K. (2021). Running Rotterdam: On how locals' participation in running events fosters their sense of place. *GeoJournal, 86*(2), 963–978. https://doi.org/10.1007/s10708-019-10104-3

Völker, S., & Kistemann, T. (2013). "I'm always entirely happy when I'm here!" urban blue enhancing human health and well-being in Cologne and Düsseldorf, Germany. *Social Science & Medicine, 78*(1), 113–124. https://doi.org/10.1016/j.socscimed.2012.09.047

Völker, S., & Kistemann, T. (2015). Developing the urban blue: Comparative health responses to blue and green urban open spaces in Germany. *Health & Place, 35*, 196–205. https://doi.org/10.1016/j.healthplace.2014.10.015

Wang, J. (2023). The digital presentation of human-oriented urban design. *Sustainable Cities and Society, 97*(April), Article 104746. https://doi.org/10.1016/j.scs.2023.104746

Wang, R., & Zhao, J. (2017). Demographic groups' differences in visual preference for vegetated landscapes in urban green space. *Sustainable Cities and Society, 28*, 350–357. https://doi.org/10.1016/j.scs.2016.10.010

Wang, S., Wang, M., & Liu, Y. (2021). Access to urban parks: Comparing spatial accessibility measures using three GIS-based approaches. *Computers, Environment and Urban Systems, 90*, Article 101713. https://doi.org/10.1016/j.compenvurbsys.2021.101713

Wang, Y., Chau, C. K., Ng, W. Y., & Leung, T. M. (2016). A review on the effects of physical built environment attributes on enhancing walking and cycling activity levels within residential neighborhoods. *Cities, 50*, 1–15. https://doi.org/10.1016/j.cities.2015.08.004

Ward, M. D., & Gleditsch, K. S. (2019). *Spatial Regression Models*. SAGE Publications, Inc.. https://doi.org/10.4135/9781071802588

White, M. P., Elliott, L. R., Gascon, M., Roberts, B., & Fleming, L. E. (2020). Blue space, health and well-being: A narrative overview and synthesis of potential benefits. *Environmental Research, 191*(August), Article 110169. https://doi.org/10.1016/j.envres.2020.110169

White, M. P., Wheeler, B. W., Herbert, S., Alcock, I., & Depledge, M. H. (2014). Coastal proximity and physical activity: Is the coast an under-appreciated public health resource? *Preventive Medicine, 69*, 135–140. https://doi.org/10.1016/j.ypmed.2014.09.016

WHO. (2020). *Healthy cities effective approach to a rapidly changing world*. World Health Organization. https://apps.who.int/iris/bitstream/handle/10665/331946/9789240004825-eng.pdf.

WHO. (2021). *Green and blue spaces and mental health new evidence and perspectives for action (issue July)*. World Health Organization Regional Office for Europe.

Xiang, Y., Hedblom, M., Wang, S., Qiu, L., & Gao, T. (2022). Indicator selection combining audio and visual perception of urban green spaces. *Ecological Indicators, 137*(March), Article 108772. https://doi.org/10.1016/j.ecolind.2022.108772

Yang, H., Zhang, Q., Helbich, M., Lu, Y., He, D., Ettema, D., & Chen, L. (2022). Examining non-linear associations between built environments around workplace and adults' walking behaviour in Shanghai, China. *Transportation Research Part A: Policy and Practice, 155*(April 2021), 234–246. https://doi.org/10.1016/j.tra.2021.11.017

Yang, L., Yu, B., Liang, P., Tang, X., & Li, J. (2022). Crowdsourced data for physical activity-built environment research: Applying Strava data in Chengdu, China. *Frontiers in Public Health, 10*. https://doi.org/10.3389/fpubh.2022.883177

Zhang, A., Song, L., & Zhang, F. (2022). Perception of pleasure in the urban running environment with street view images and running routes. *Journal of Geographical Sciences, 32*(12), 2624–2640. https://doi.org/10.1007/s11442-022-2064-8

Zhang, H., Nijhuis, S., & Newton, C. (2022). Freshwater blue space design and human health: A comprehensive research mapping based on scientometric analysis. *Environmental Impact Assessment Review, 97*, Article 106859. https://doi.org/10.1016/j.eiar.2022.106859

Zhang, H., Nijhuis, S., & Newton, C. (2023a). Uncovering the visibility of blue spaces: Design-oriented methods for analysing water elements and maximising their potential. *Journal of Digital Landscape Architecture, 2023*(8). https://doi.org/10.14627/537740066, 628–638.

Zhang, H., Nijhuis, S., & Newton, C. (2023b). Advanced digital methods for analysing and optimising accessibility and visibility of water for designing sustainable healthy urban environments. *Sustainable Cities and Society, 98*(June), Article 104804. https://doi.org/10.1016/j.scs.2023.104804

Zhang, H., Nijhuis, S., Newton, C., & Tao, Y. (2024). Healthy urban blue space design: Exploring the associations of blue space quality with recreational running and cycling using crowdsourced data. *Sustainable Cities and Society, 117*(February), Article 105929. https://doi.org/10.1016/j.scs.2024.105929

Zijlema, W. L., Triguero-Mas, M., Smith, G., Cirach, M., Martinez, D., Dadvand, P., … Julvez, J. (2017). The relationship between natural outdoor environments and cognitive functioning and its mediators. *Environmental Research, 155*(March), 268–275. https://doi.org/10.1016/j.envres.2017.02.017

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