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Review

Pedestrian Emotion Perception in Urban Built Environments Based on Virtual Reality Technology: A Comparative Review of Chinese- and English-Language Literature

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Abstract

The built environment plays a crucial role in shaping residents' quality of life and emotional well-being. In the context of growing efforts to promote livable and walkable cities, a key question emerges: how can emerging technologies—particularly virtual reality (VR)—be leveraged to evaluate and enhance urban environments through the lens of pedestrian emotional perception? This study systematically reviewed the literature published between 2015 and 2024 in the China National Knowledge Infrastructure (CNKI) and Web of Science (WOS) databases, ultimately identifying 37 Chinese-language and 113 English-language journal articles. Using bibliometric analysis and CiteSpace, the research mapped publication trends, research hotspots, and disciplinary networks across linguistic contexts. Results reveal that Chinese-language studies often emphasize embodied cognition and electroencephalogram (EEG) monitoring, while English-language studies focus more on VR application in stress recovery and health assessment. Based on this synthesis, this study proposes a "sensory–cognitive–affective" framework and a set of spatial intervention strategies, offering a novel perspective for emotion-driven urban design. The findings highlight a paradigm shift from engineering-oriented planning to human-centered approaches, with VR technologies serving as a critical enabling tool. This review contributes both conceptual and methodological foundations for future research at the intersection of immersive technologies, built environment studies, and urban emotional well-being.

Keywords: virtual reality (VR); urban streetscape; human-centered design; built environment; emotional perception

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1. Introduction

In the context of urbanization and digitalization, research on pedestrian emotion perception holds profound theoretical and practical significance. It plays a key role in enhancing residents' quality of life, public health, and urban planning. Emotional states directly influence individuals' mental and physical well-being, expand cognitive capacities, and help build lasting personal resources. These emotional factors contribute to greater psychological resilience and foster social harmony and cooperation [1]. In public health, emotion research supports the development of therapeutic applications. In urban planning,

it enables designers and policymakers to more accurately understand residents' needs and preferences [2].

The quality of the built environment significantly shapes pedestrians' emotional perception. It also constitutes a key element of urban placemaking and directly impacts urban residents' well-being and life satisfaction [3]. Elements such as comfort, safety, and aesthetics in the built environment exert profound effects on emotional responses [4]. Existing studies have shown that well-designed built environments can reduce stress and negative emotions, alleviate mental fatigue, and promote both psychological and physical health [5].

Foundational urban theory—particularly Kevin Lynch's work on the imageability of the city—has demonstrated that spatial elements such as paths, edges, districts, nodes, and landmarks fundamentally shape individuals' mental maps and emotional experiences of urban spaces [6]. However, traditional research methods often struggle to capture these emotional effects in ecologically valid and measurable ways [7,8]. This limitation arises from several factors: self-report biases inherent in surveys [9], the difficulty of isolating environmental variables in field studies [10], and the challenge of detecting subconscious emotional responses [11].

In recent years, virtual reality (VR) technology has been increasingly applied in urban planning and design. It allows designers and researchers to simulate and reconstruct immersive street environments, enabling more precise assessments of their emotional impacts. VR environments support user engagement by enhancing presence, interaction, and enjoyment [12]. Compared with traditional methods, VR offers a more realistic and controlled testing ground. It also enables more accurate observation and documentation of pedestrian behavior, thereby improving research credibility and validity [13]. Additionally, VR can be integrated with wearable physiological sensors to capture emotional feedback, providing data-driven evidence to support improvements in street-level design.

Over the past three decades, China has experienced rapid and large-scale urbanization, which has profoundly reshaped its built environment and created unique socio-spatial challenges [14]. The development of VR technologies in this context offers new opportunities to study the emotional dimension of urban experience [15]. English-language scholarship entered this field earlier and has largely focused on topics such as health promotion, stress recovery, and policy evaluation. In contrast, Chinese-language studies have emerged more recently and often emphasize topics grounded in local conditions-such as therapeutic street design, embodied cognition, and the emotional impacts of rapid urban renewal.

Given the differences in historical trajectories, research priorities, and methodological approaches, a systematic comparison between Chinese- and English-language studies is both timely and necessary. Comparative analysis helps reveal convergence and divergence across linguistic and cultural research traditions, and it also bridges knowledge gaps between global and local contexts. More importantly, such a perspective offers critical insights into how international theories and methods can be contextualized for China's unique urban conditions. Ultimately, this comparative lens contributes both theoretical depth and practical value to the development of sustainable and human-centered urban environments.

This review adopts a dual-method approach, integrating bibliometric mapping with qualitative analysis to systematically examine Chinese- and English-language literature. The analysis is organized around three pivotal themes: (1) mechanisms of environmental-emotional interaction, (2) VR-enabled spatial intervention strategies, and (3) implications for urban policy. Furthermore, this study explores the evolving role of VR technology in this domain. Through this structured investigation, this paper highlights how research on pedestrian emotion perception not only reshapes urban design methodologies but also

drives a paradigm shift in planning and policy—from an engineering-oriented model to a human-centered approach.

2. Methods and Data

2.1. Research Framework

The research framework of this study is illustrated in Figure 1 and follows a four-step process. First, relevant literature was retrieved and screened from two major databases: Web of Science (WOS) and China National Knowledge Infrastructure (CNKI), which is the most comprehensive database for Chinese-language scholarly publications. This step provided the initial dataset. Second, bibliometric analysis was conducted to map the knowledge structure and identify major research trends. Third, qualitative analysis was used to interpret the findings in greater depth, focusing on research themes, methodological approaches, and the application of VR technology in built environment studies. Finally, this study integrated the results from both analyses to draw key conclusions and propose directions for future research.

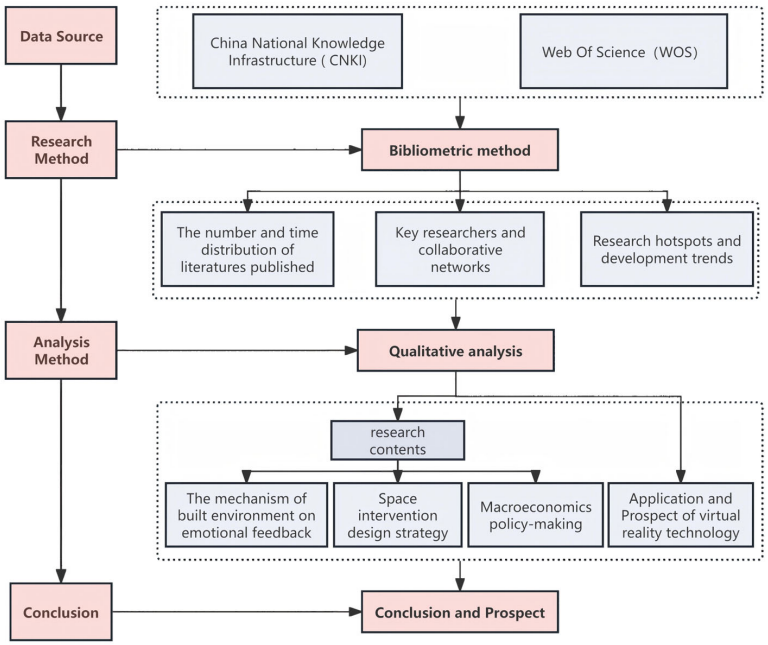


Figure 1. Research framework.

2.2. Methods

This study applied bibliometric and qualitative analysis methods, using visual tools to examine patterns in the literature. Bibliometric analysis was first conducted using CiteSpace (6.3.R1), which generated author collaboration networks, keyword co-occurrence maps, and other visualizations to summarize and extract key themes from the selected publication [16]. As a knowledge-mapping tool, CiteSpace offers more diverse and insightful visual representations than traditional techniques and is widely used across various academic disciplines [17]. Based on the visualization results, qualitative analysis was then applied to explore key differences and similarities between Chinese- and English-language literature, identify major research themes, and assess the current applications and future potential of VR technology in the study of built environments and pedestrian emotion.

2.3. Data Source

The data for this study were collected from the CNKI and the WOS databases. Keyword combinations included terms such as “virtual reality,” “emotion,” “built environ-

ment," and "urban." In CNKI, the search formula was: (topic: emotion + affect + emotional perception) AND (topic: urban + street + streetscape). In WOS, the search formula was: (((((((TS = (Emotion)) OR TS = (Mood)) OR TS = (Sentiment)) OR TS = (Emotional state)) OR TS = (Emotional response)) OR TS = (Sentimental value)) AND TS = (Built Environment)) AND TS = (Urban)) OR TS = (Street). To reflect recent developments and technological advancements, this study focused on literature published between 2015 and 2024 to explore research trends over the past decade.

The initial CNKI search returned 11,400 records. After filtering out non-journal publications-such as news articles, conference proceedings, books, and yearbooks- and narrowing the subject category to "Architecture Science and Engineering," 625 Chinese-language journal articles remained. In WOS, the initial search within the Core Collection retrieved 113,200 records. These results were refined by limiting the research areas to "Environmental Science Ecology," "Engineering," "Public Environmental Occupational Health," "Behavioral Sciences," and "Urban Studies," resulting in 2095 English-language journal records. Following a manual screening process to exclude unrelated literature to the research focus, the final dataset included 37 Chinese-language articles from CNKI and 113 English-language articles from WOS.

3. Analysis of Chinese-Language and English-Language Research Status

3.1. Temporal Distribution of Publications

Over the past decade, research on pedestrian emotion perception in urban built environments using VR technology has gained increasing attention, as reflected in the temporal distribution of publications shown in Figure 2. From 2015 to 2018, studies in this field were still in their early stages, with relatively few publications in both Chinese- and English-language literature. A notable increase began in 2019, particularly in English-language research, which peaked in 2021 and 2023. This surge highlights the growing global interest in applying immersive technologies to urban and emotional studies. Chinese-language publications, although smaller in volume, have also shown steady growth from two articles in 2018 to six in 2023. The slight decline observed in 2024 for both language categories is likely due to recent research not yet being published or indexed at the time of data collection. Overall, Figure 2 illustrates a sustained upward trajectory in publication activity, confirming the expanding role of VR technology in this interdisciplinary domain. The increasing number of studies in both Chinese- and English-language sources reflects a shared recognition of the importance of emotional perception in urban environments and the value of immersive tools in advancing this field.

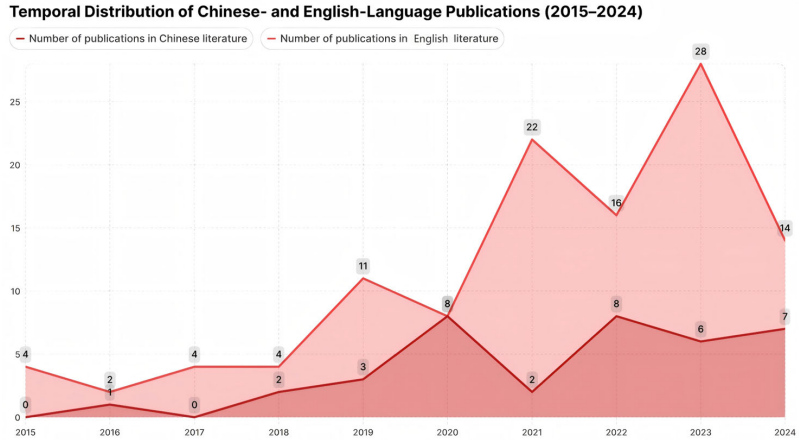


Figure 2. Temporal distribution of publications in Chinese-language and English-language literature (2015–2024).

3.2. Major Research Contributors and Collaboration Networks

Based on CiteSpace analysis of the 37 Chinese-language articles, the author collaboration network comprises 105 nodes and 152 links, with a network density of 0.0278. This relatively low density suggests that while a number of researchers are involved in the field, close collaboration among them remains limited. As shown in Figure 3, Leiqing Xu (4 publications) and Zheng Chen (3 publications), both affiliated with Tongji University, are the most productive authors and serve as central figures in the network. These core researchers play a key role in shaping the development of VR-related research on pedestrian emotion within Chinese-language literature and reflect the concentration of academic activity around a few leading institutions.

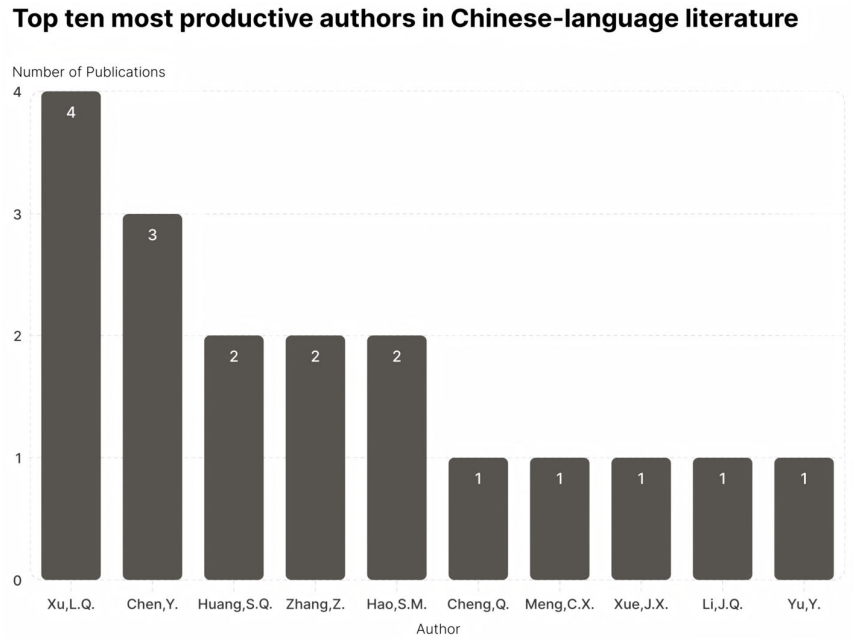


Figure 3. Top ten most productive authors in Chinese-language literature.

The institutional collaboration network for the 37 Chinese-language articles is illustrated in Figure 4. The analysis shows that the majority of prolific institutions are schools of architecture or urban planning within Chinese universities. The College of Architecture and Urban Planning at Tongji University stands out as the most productive institution, contributing 7 publications, and is the most active in academic collaboration within the network. Other institutions with notable contributions include the College of Architecture and Urban Planning at Beijing University of Civil Engineering and Architecture and the College of Arts and Media at Tongji University, each contributing 2 publications. Despite these contributions, the overall institutional collaboration network remains relatively fragmented. The data suggest strong intra-institutional collaboration, particularly within Tongji University, but limited inter-institutional or cross-team cooperation across the broader network. This indicates potential for further development in expanding national and regional research partnerships within the Chinese-language academic community.

Similarly, CiteSpace analysis of the 113 English-language articles generated a network with 221 nodes and 290 links, with a network density of 0.0119 (Figure 5). This indicates a relatively sparse network structure, suggesting that while many authors are contributing to this field, collaborative ties across research groups remain limited. Notable contributors include Wenyi Dong, Antonio Fernandez-Caballero, and Florent Robert, each of whom has published more than two articles and made significant contributions to the development of research on pedestrian emotion and the built environment. As shown in Figure 5,

the structure of the English-language author network is more globally distributed than its Chinese-language counterpart, involving researchers from diverse institutions and countries. However, the overall connectivity remains relatively low, indicating substantial room for strengthening international research collaboration and fostering more cohesive academic communities around this interdisciplinary topic.

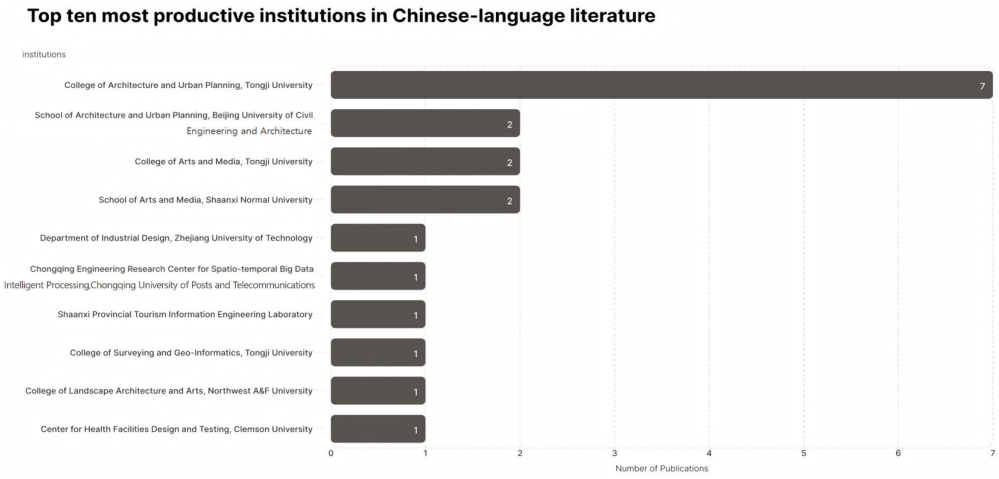


Figure 4. Top ten most productive institutions in Chinese-language literature.



Figure 5. Author collaboration network in English-language literature.

Institutional collaboration analysis for the 113 English-language articles is presented in Figure 6. The results shows that Beijing Forestry University leads with 4 publication, followed by the French National Centre for Scientific Research (CNRS) and Hanyang University, each contributing 3 publications. Despite this geographic diversity, the institutional collaboration network remains relatively sparse, with a network density of 0.0126.

To further explore global research dynamics, CiteSpace was used to visualize the distribution of publications and collaborations within the English-language dataset (Figure 7). The results show that China had the highest number of publications, reflecting substantial research activity in the field, followed by the United States, which also demonstrated high output and impact. Other key contributing countries include Australia, the United Kingdom, and Germany.

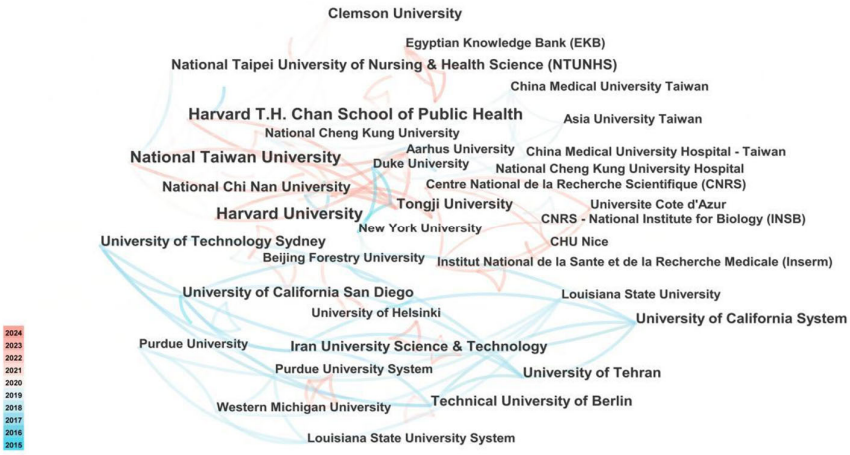


Figure 6. Institutional collaboration network in English-language literature.

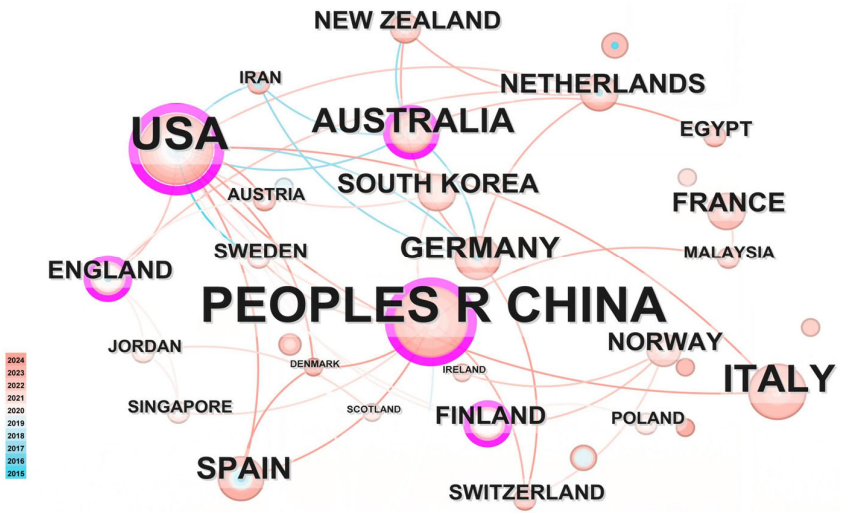


Figure 7. Country-level publication counts and collaboration network in English-language literature.

As shown in Table 1, the top ten countries in terms of publication volume and betweenness centrality were identified. Although China ranked first in publication count, its centrality was significantly lower than that of the United States, which ranked second in publication volume. This suggests that while China is highly productive in this field, its research is less integrated into the global collaboration network. In contrast, the United States' high publication count, combined with extensive international partnerships, places it at the center of the global research network.

Table 1. Top ten countries by publication count and betweenness centrality.

Rank	Publications	Centrality	Country
1	26	0.29	China
2	19	0.57	USA
3	11	0.00	Italy
4	10	0.10	Australia
5	6	0.07	Germany
6	6	0.00	Spain
7	5	0.00	France
8	5	0.00	South Korea
9	5	0.04	Netherlands
10	4	0.13	UK

This gap in centrality highlights a strategic shortcoming. Without robust international collaboration, Chinese research risks reduced visibility, fewer citations, and limited influence in shaping global academic discourse. Strengthening cross-border collaboration—through joint publications, international projects, and researcher exchanges—would not only improve China's betweenness centrality but also enhance its role in global research leadership. Given China's strong domestic output, expanding international engagement is a critical next step for amplifying scholarly impact and promoting the global dissemination of its research.

3.3. Research Hotspots and Development Trends

3.3.1. Research Hotspots

Keywords provide a concise representation of the core content of academic publications [18], and keyword co-occurrence analysis helps to identify research focuses and emerging trends within a field [19]. Based on CiteSpace analysis of the 37 Chinese-language articles, the resulting keyword co-occurrence network includes 90 nodes and 176 links, with a network density of 0.0439 (Figure 8). This relatively high density suggests strong thematic interconnectivity and frequent collaboration among researchers working on related topics. As shown in Figure 8, the most frequently occurring keywords in the Chinese-language literature are "virtual reality," "healing environments," "emotion," "electroencephalogram (EEG) signals," and "embodied cognition." These keywords reflect the field's current research focus on integrating immersive technologies with psychological and physiological measurements to assess the emotional impact of urban environments. The dense clustering of terms further indicates that these topics are often explored in combination, pointing to a maturing research area characterized by interdisciplinary integration.

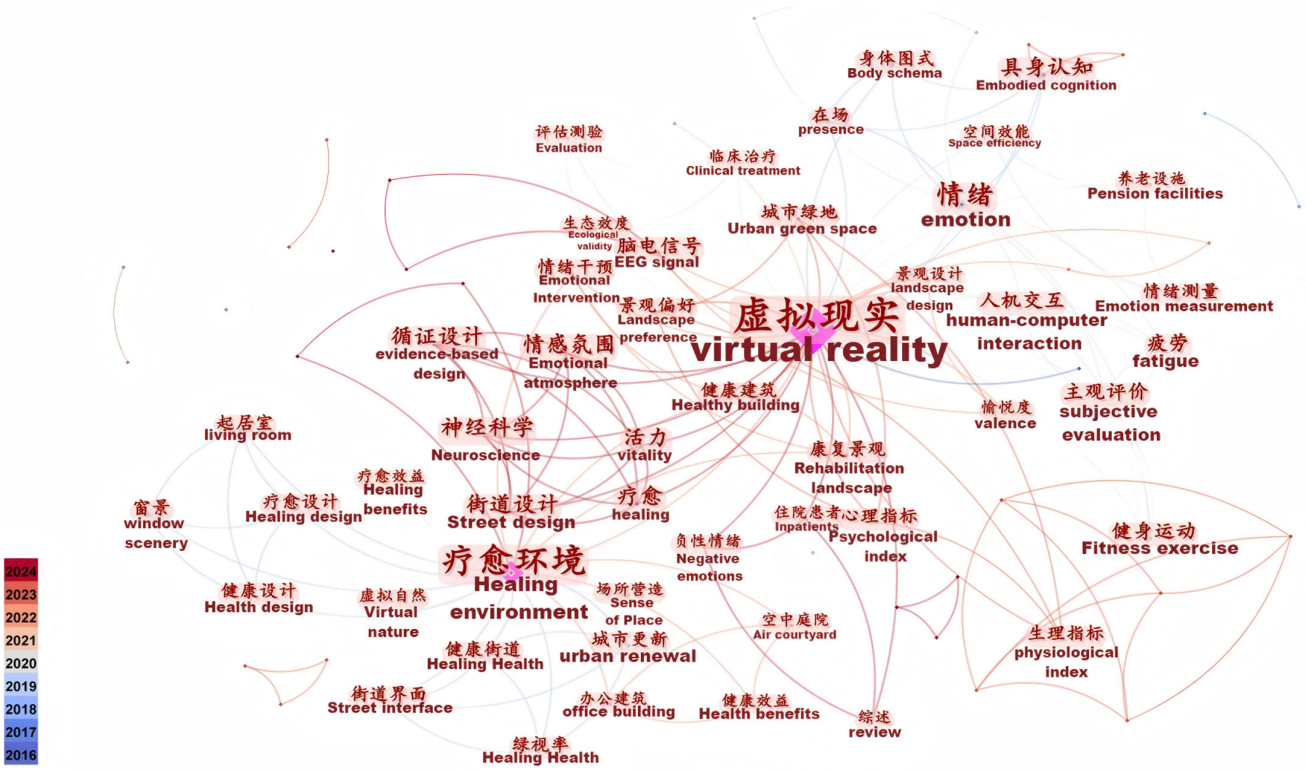


Figure 8. Keyword co-occurrence network in Chinese-language literature.

Keyword co-occurrence analysis of the 113 English-language articles produced a network with 257 nodes, 908 links, and a density of 0.0276 (Figure 9), indicating a wide range of topics but relatively loose thematic integration. Core keywords include "virtual

reality," "stress recovery," "environments," "health," and "perception," reflecting a strong focus on how VR and built environments influence emotional responses and pedestrian behavior. The frequent pairing of "virtual reality" with "built environments" and "behavior" highlights VR's growing role as an evaluation tool. Keywords such as "exposure" and "stress recovery" suggest sustained interest in health impacts of environmental factors. The lower density points to opportunities for stronger cross-topic collaboration.

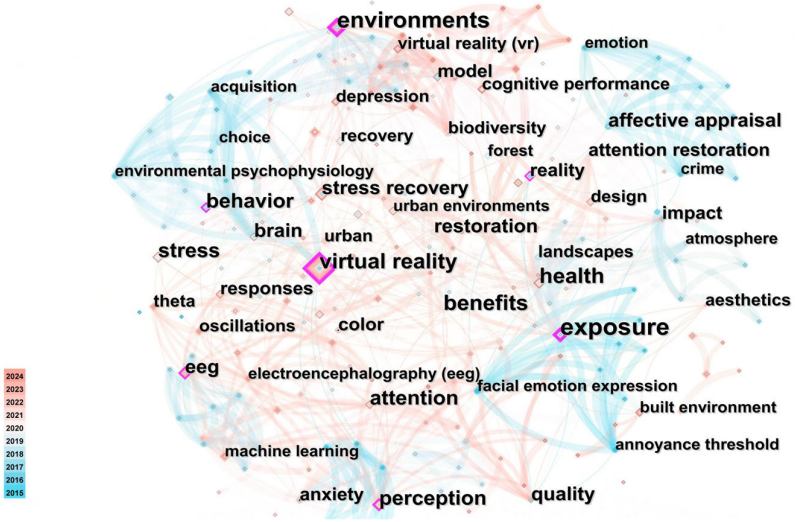


Figure 9. Keyword co-occurrence network in English-language literature.

The centrality of a keyword reflects its importance in connecting different research themes within the co-occurrence network [20]. Table 2 lists the top ten most frequently occurring keywords in the English-language literature. "Virtual reality" ranks first in both centrality (0.24) and co-occurrence frequency (57), underscoring its pivotal role in this research domain. It is followed by "exposure" (centrality 0.21) and "environments" (centrality 0.23), both of which also show high centrality, indicating their significance in shaping research context and methodology. These results confirm that VR is a central tool in the study of how environmental exposure influences emotional and behavioral responses.

Table 2. Top ten high-frequency keywords in English-language literature.

Rank	Frequency	Centrality	Keyword
1	57	0.24	virtual reality
2	17	0.21	exposure
3	16	0.05	stress recovery
4	14	0.23	environments
5	12	0.08	health
6	11	0.08	benefits
7	11	0.11	perception
8	9	0.15	behavior
9	8	0.09	stress
10	8	0.06	model

3.3.2. Development Trends

A review of the 37 Chinese-language articles published over the past decade reveals three dominant research themes: "virtual reality technology," "healing environments," and "emotion." Among these, VR technology serves as the foundational tool, supporting immersive experimentation and evaluation in emotional perception studies.

Many studies investigate how the design and optimization of healing environments can improve mental health and emotional states. Creating healing environments is one of the major research objectives in this domain and holds important implications for optimizing urban design and enhancing public health and well-being. For instance, Xu et al. (2019) assessed the restorative potential of different urban street environments and green view indices using VR technology, physiological data, and psychological measurement tools such as the Perceived Restorativeness Scale [21]. Researchers have employed various technical approaches to monitor and evaluate emotional responses, aiming to optimize virtual environment design to enhance user experience. Emotion research has emerged as a central theme, serving as a pathway to enhance the psychological benefits of urban environments [22]. For example, Hao et al. (2023) conducted experiments with a VR-based restorative interface grounded in the environmental stress model, exploring how emotional interventions can enhance the emotional benefits of urban built environments and provide emotional support for older adults [23].

Using CiteSpace's clustering algorithm, the keyword co-occurrence network from the 113 English-language articles was grouped into eight clusters, which are synthesized here into four thematic categories. The resulting clustering timeline map is shown in Figure 10, with a modularity (Q) value of 0.4939 and mean silhouette (S) value of 0.784, indicating reliable clustering and reasonable internal consistency.

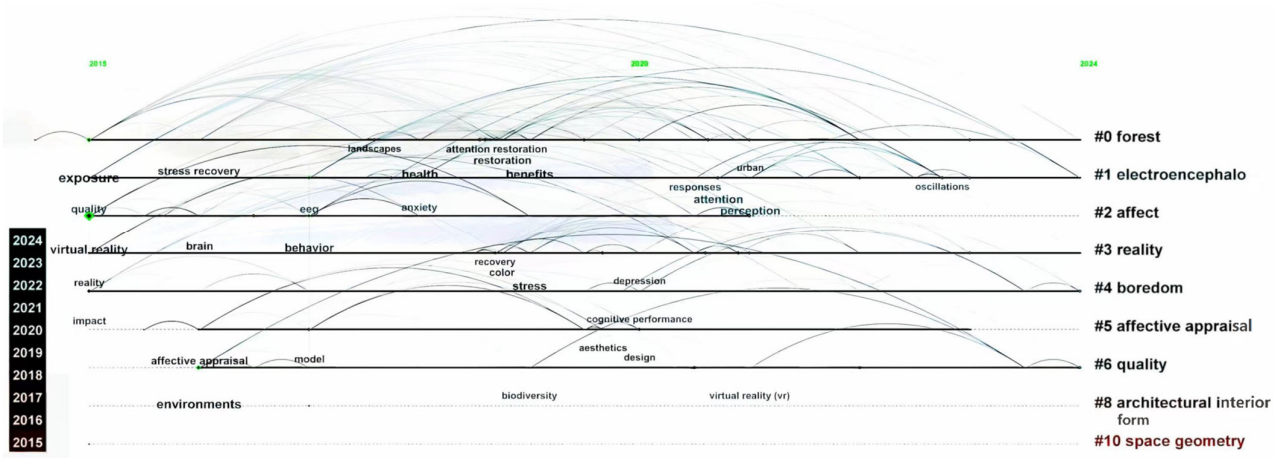


Figure 10. Keyword clustering timeline map in English-language literature.

Scope of Research: #0 Forest. This cluster focuses on the role of natural elements in urban environments, particularly urban forests and indoor green spaces, in enhancing emotional well-being. For example, Wang et al. (2024) evaluated the direct and indirect effects of natural environments on stress reduction by exposing participants to images of different types of urban forests in VR [24]. Pedestrian interactions with natural environments often evoke positive emotional responses such as relaxation and pleasure [25]. Studies have shown that urban forests can enhance mental health and reduce psychological stress [26], providing scientific evidence for sustainable urban development policies and promoting urban greening and environmental protection initiatives.

Emotion Monitoring and Evaluation: #1 Electroencephalogram (EEG), #2 Affect, #5 Affective Appraisal. These clusters focus on technologies and frameworks used to evaluate emotional responses. EEG technology is increasingly used to quantitatively measure how built environments influence affective states. For example, Abu Hasan et al. (2022) combined EEG readings with pilot studies to assess emotional impacts [27]. In recent years, the integration of electrophysiological signal measurement and VR technology has provided new tools for mental health interventions and treatments [28], aiding in the identification and manage-

ment of emotional issues. Such methods also help designers and planners better understand the needs of different individuals and groups to create more human-centered and livable urban environments.

Urban Quality of Life and VR Applications: #3 Reality, #4 Boredom, #6 Quality. This category captures the application of VR in simulating urban environments to assess and enhance emotional quality of life. For instance, Yang et al. (2024) conducted VR experiments simulating urban environments and applied emotion computation models to study the influence of different built environment factors on pedestrian emotional states [29]. The design of urban built environments significantly affects emotional states [30] such as boredom or excitement [31]. Research on reducing negative emotions and improving quality of life through design optimization has become a prominent trend in recent years.

Built Environment Factors: #8 Architectural Interior Form, #10 Space Geometry. The pedestrian experience extends beyond outdoor streets into publicly accessible interior spaces (e.g., transit hubs, retail atria), which serve as critical nodes within the urban network. Architectural interiors and spatial geometry have a direct impact on pedestrian emotions and mental health. For example, Banaei et al. (2017) used VR and Mobile Brain/Body Imaging (MoBI) technology to examine how architectural interior design and spatial geometry affect emotional responses and psychological well-being [32]. Their study demonstrated that specific spatial parameters—such as curved geometry—significantly influence neural activity in brain regions like the anterior cingulate cortex, which is associated with emotional regulation. This finding provides a neurophysiological basis for understanding how interior forms can modulate affective states. The growing academic attention to these factors reflects a more comprehensive approach to evaluating how the built environment shapes emotional well-being. Clustering results also suggest that, with ongoing technological advancement and increasing demands for quality of life, future architectural design will place greater emphasis on integrating emotional well-being and spatial efficiency.

3.4. Similarities and Differences Between Chinese-Language and English-Language Literature

We compare the characteristics of the 37 Chinese-language and 113 English-language journal articles reviewed in this study, focusing on trends, collaboration patterns, and thematic orientations. A summary of the key distinctions is presented in Table 3.

Table 3. Descriptive comparison of Chinese and English-language literature.

Aspect	Chinese-Language Literature	English-Language Literature
General Trend	Demonstrates rapid growth in recent years and has emerged as a new research hotspot.	Entered the field earlier and maintains a clear numerical advantage in publication volume.
	Both bodies of literature reflect a significant rise in scholarly interest in this topic.	
Collaboration Networks	Characterized by tightly-knit collaboration, primarily among domestic universities and research institutes.	Features more geographically dispersed international collaborations, although with a relatively looser structure.
	Core research groups are identifiable in both contexts.	
Research Hotspots	Emphasizes technological applications (e.g., EEG, eye-tracking) and the design of healing environments.	Focuses more on stress recovery public health evaluation, and broader scenario-based applications.
	Both emphasize the role of VR in understanding pedestrian emotion and its urban applications.	

As shown in Table 3, both Chinese- and English-language studies share a common recognition of VR's potential for understanding pedestrian emotional perception in urban contexts. However, they diverge in their thematic emphases and methodological orientations.

This comparative analysis highlights meaningful differences in research priorities between the two bodies of literature. It is important to clarify that the WoS database includes significant contributions from scholars publishing in English. Therefore, this comparison focuses not on national output, but on the linguistic and discursive patterns of academic communication within each domain.

Crucially, these divergences are not coincidental but reflect deeper contextual drivers. The predominance of stress recovery in English-language literature aligns with the long-standing influence of public health discourses in Western planning traditions, which often focus on mitigating environmental stressors. Conversely, the Chinese-language literature's emphasis on healing environments and physiological monitoring is shaped by several factors, including policy direction, technological advancement and cultural orientation. Recognizing these underlying drivers is essential for interpreting the evolution of this interdisciplinary field. It also opens opportunities for mutual learning—whereby each scholarly tradition can inform the other, fostering more nuanced, inclusive, and context-sensitive approaches to understanding how urban environments affect human emotion.

4. Discussion

4.1. Mechanism Linking Built Environment and Emotional Feedback

A core objective of this research field is to uncover how the built environment shapes pedestrian emotions, with the goal of providing a theoretical foundation for evidence-based urban design. This relationship can be conceptualized as a three-stage mechanism: sensory stimulation, cognitive appraisal, and affective response (Figure 11).

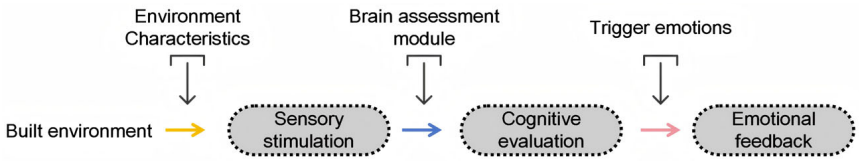


Figure 11. Sensory stimulation—cognitive appraisal—affective response framework.

In the first stage, environmental features—such as green view index and spatial openness—activate multiple sensory pathways (e.g., visual, auditory), triggering physiological responses such as changes in heart rate or skin conductance [33]. In the second stage, individuals cognitively evaluate these environments based on perceived safety, functional adaptability, and aesthetic preference [34]. In the final stage, these appraisals lead to either positive or negative emotional responses, such as pleasure, stress relief, discomfort, or suppression.

VR technology plays a critical role in this three-stage model by enabling variable isolation and causal verification, as well as integrating multi-source datasets [35], thereby enhancing the scientific rigor of explanations regarding the mechanism.

This mechanism demonstrates strong explanatory power and practical values across diverse application contexts. As summarized in Table 4, it offers theoretical enrichment to the field of environmental psychology by linking built environment features with emotional responses. These findings address the importance of integrating emotion-oriented models into future research and practice in urban design.

Table 4. Mechanisms linking built environment and emotional response.

Application Area	Mechanistic Pathway	VR Application and Methods	Typical Case
Mental health intervention	Restorative environmental stimuli activate the parasympathetic nervous system [36].	Restorative environments built on the Unity engine, enabling human–computer interaction design.	Wang Zhimeng et al. (2022) developed a virtual park in Unity for individuals with mild-to-moderate depression, reducing SDS scores ($p = 0.017$); watering activity reduced depression by 21% ($p = 0.013$) [37].
Physical health promotion	Reduction of stress hormone levels [38].	Construction of contrast scenes with environmental parameter control and real-time physiological monitoring.	Salgado-Pineda P. et al. (2023) found that a beach VR scene reduced systolic blood pressure by 12 mmHg, outperforming urban scenes ($\Delta = 7.2$ mmHg, $p < 0.05$) [39].
Cognitive resource optimization	Reduction of prefrontal cortex cognitive load [40].	Multivariate orthogonal experiments integrating eye-tracking and neural activity monitoring.	Zhang Yalin (2024) showed that when the window-to-wall ratio in classrooms was 30%, Stroop test error rates decreased by 21%, and sustained attention increased by 43% [41].
Commercial value enhancement	Increased emotional appeal of environments [42].	Spatial experience simulation with user behavior heatmapping and decision path analysis.	Maurizio Mauri (2024) found that VR-based property viewing shortened decision time by 58% and increased transaction rates by 33% [43].
Cultural identity building	Activation of collective memory and emotional resonance [44].	Reconstruction of 3D scenes integrated with emotional semantics and spatial optimization validation.	In the Shanghai Gongkang Road micro-renewal project, VR-based emotional mapping raised residents' place identity scores from 2.8/5 to 4.1/5 (Zhang Zhen et al., 2024) [45].
Support for special populations	Customized sensory–cognitive matching strategies [46].	Closed-loop neurofeedback monitoring with longitudinal intervention assessment.	Abu Hasan et al. (2022) developed an EEG–VR training system for preschool educators, improving psychological resilience scores by 29% and reducing occupational burnout incidence by 41% [27].

4.2. Spatial Intervention Design Strategies

Recent advances in this field offers new tools and methods for innovating urban planning and design. By quantitatively evaluating pedestrians' emotional responses, the field supports a shift from experience-based to evidence-based design [47]. VR technology plays a central role in this transformation by enabling controlled manipulation of spatial elements and dynamic feedback loops, thus informing design decisions with measurable emotional data.

In terms of manipulating street elements, VR environments allow designers to simulate diverse configurations—such as variations in green view indices, street interfaces, and public facility layouts. When combined with data collection methods such as questionnaires, interviews, and physiological sensors, this allows for the identification of quantitative relationships between environmental factors and emotional responses [48]. For example, Zhang et al. (2021) integrated VR with EEG, electrodermal activity (EDA), and heart rate monitoring to examine how global spatial layout and color composition in streetscapes affect emotional responses, revealing notable discrepancies between physiological indicators and subjective evaluations [49]. In their study, participants were immersed in a series of urban street scenes through VR while their EEG and EDA signals were synchronously recorded. The key innovation lay in the application of global landscape metrics to quantitatively assess the visual patterns of streetscapes, moving beyond traditional element-based analysis. The statistical results showed that more diverse and less fragmented visual configurations were significantly associated with positive emotional responses. Moreover, this study uncovered inconsistencies between physiological arousal and self-reported preference, offering a neurophysiological perspective on the classic form-function dichotomy in architecture. Overall, this research demonstrates how VR, combined with physiological sensing can provide designers with quantifiable, causal evidence on how specific spatial configurations shape human emotion, thereby supporting data-informed optimization of street

design parameters. Furthermore, embedding local cultural symbols in VR scenes—such as traditional facades, street furniture, and pavement patterns [50]—can strengthen place identity. Xu et al. (2023) tested the coexistence of architectural symbols from different historical periods, identifying an optimal emotional response range for blending old and new [51].

Regarding dynamic feedback for design optimization, VR simulations can model variations in street cross-sections, sidewalk widths, and height-to-width ratios. By integrating pedestrian trajectory data with emotional response metrics, designers can refine layouts more efficiently. For instance, Yao et al. (2021) simulated different spatial configurations of underground commercial streets in VR, quantifying the effects of street height, width, and height-to-width ratio on the Effective Stay Activity Coefficient (ESAC) and purchase intention [52]. In addition, simulating perceptual differences among specific groups—such as older adults and children—provides scientific support for differentiated design parameters. Hao et al. (2023) modeled walking-obstacle scenarios for older adults in VR, quantifying the influence curves of handrail height and obstacle warning spacing on anxiety indices [53].

4.3. Macro-Level Policy Development

Research on pedestrian emotion perception is reshaping urban design not only at the micro level but also at the macro policy level, driving a shift from traditional engineering-oriented approaches to human-centered planning. This paradigm shift is evident in the integration of evidence-based decision-making tools [54], the establishment of collaborative governance frameworks [55], and the deployment of intelligent monitoring systems [56]. VR technology plays a key role in this transformation by supporting risk prediction, cost control [57], and enhanced public participation visualization.

Evidence-based decision-making tools—such as VR scenario simulations and wearable devices for collecting stress and pleasure indices—have been incorporated into policy formulation [58], supplementing traditional planning indicators like population density and land use type. A representative application was documented in a study on the redesign of a public park in The Hague, where VR was employed to present three design alternatives to the community for a formal ballot [59]. This approach enabled a comparative analysis of engagement levels across different presentation media, with statistical results indicating that participants using VR headsets reported a significantly higher Net Promoter Score than those relying on 2D paper plans. The process generated a robust dataset of more than 1300 votes, effectively translating subjective resident preferences into a quantifiable evidence base for final decision-making. This case illustrates how VR technology can serve as a rigorous data-collection and participatory design tool, providing empirical validation for public investment decisions and grounding policy outcomes in directly measured civic input.

VR technology can also facilitate the development of collaborative governance frameworks by constructing virtual city twin models that integrate data from urban planning, public health, and transportation sectors [60]. Such frameworks support the creation of joint "emotion-health-space" governance systems, incorporating emotional health into multi-sector agendas and addressing blind spots in assessing the social benefits of traditional planning.

The emergence of intelligent monitoring systems allows for dynamic evaluation and adaptive optimization of policy outcomes [61]. A notable example is China's 2024 rollout of the "1 + 8" spatial planning algorithm suite, which includes the "Urban Residents' Online Emotional Perception Model." This model uses natural language processing (NLP) to analyze social media text, identifying emotional hotspots and underserved areas—such as

neighborhoods with frequent complaints about education or healthcare access [62]. Such tools contribute to the smart transformation of planning implementation and monitoring.

These developments deepen the theoretical foundation for healthy city planning and offer practical pathways for building more inclusive, responsive, and human-centered urban policies. They reflect a growing recognition that emotional well-being is not only a personal concern but a vital metric for social equity and public value in contemporary urban governance.

4.4. Applications and Prospects of Virtual Reality Technology

VR technology offers significant advantages in environmental simulation control and objectivity data collection [63], providing technical support for exploring the mechanisms between the built environment and pedestrian emotions, designing spatial interventions, and informing policy development.

Despite its innovative potential, several limitations remains in its application to urban and emotional research. These include challenges related to ecological validity, hardware compatibility, and simulator sickness [64]. Ecological validity is constrained by the inability of current VR systems to fully replicate multisensory stimuli such as temperature and scent. This can be improved by integrating haptic feedback gloves and olfactory generators, which enhance multimodal immersion [65–67]. Hardware compatibility challenges highlight the urgent need for cross-platform standardized protocols to unify data collection specifications [68]. Additionally, progressive exposure training can effectively reduce the incidence of simulator sickness among participants [69]. These limitations indicate the necessity of remaining vigilant to potential biases and challenges in VR applications and adopting measures to improve research accuracy.

VR is poised to evolve beyond a simulation tool into an interdisciplinary platform connecting neuroscience, public health, and spatial governance.

In neuroscience, the integration of VR with emerging brain–computer interface technologies—such as high-resolution electrocorticography (ECoG) [70]—offers new opportunities to uncover the neural encoding patterns underlying spatial anxiety. This prospective case study proposes a paradigm that combines VR with high-density ECoG to decode the neural mechanisms associated with anxiety in urban environments. Participants would navigate virtual simulations of diverse urban streetscapes while their brain activity is continuously monitored. The core objective is to identify specific neural oscillation patterns in regions such as the amygdala that correlate with anxiety triggered by environmental attributes like spatial enclosure and limited visibility. The expected outcome is the derivation of a quantitative neural signature for spatial anxiety, advancing beyond subjective self-report methods. Ultimately, this line of research aims to establish a neurophysiological evidence base to guide the design of urban environments that proactively mitigate negative emotional responses.

In public health, VR could be used to build dynamic epidemiological models, simulating viral aerosols dispersion under various urban morphologies to inform pandemic-resilient spatial design. Further integration with urban digital twin platforms (e.g., CityGML 3.0) would allow researchers to embed real-time emotional data streams into dynamic “emotion-space” feedback models, enabling responsive urban planning based on collective affective states. These interdisciplinary innovations indicate a shift toward using VR not only for environmental assessment but also as a strategic tool in human-centered, data-driven urban transformation.

5. Conclusions and Future Envision

This study provides a comprehensive review of how VR technology has been applied in research on pedestrian emotion perception within urban built environments from 2015 to 2024. Drawing on 150 articles retrieved from the CNKI and WOS databases, we combined bibliometric analysis and qualitative synthesis to explore publication trends, collaboration patterns, thematic clusters, and methodological developments. The findings offer new insights into the evolving landscape of this interdisciplinary field and suggest promising directions for future innovation.

Publication Patterns and Research Networks: English-language literature dominates in scale and has shown sustained growth over the past decade. Chinese-language research, while emerging later, has expanded rapidly since 2018. Collaboration networks also differ. Chinese research demonstrates strong disciplinary cohesion within architecture and planning, while international networks are more interdisciplinary and globally distributed. Given China's leading publication volume but relatively lower international centrality, strengthening global research partnerships is not only necessary but strategic. Expanding international collaboration would enhance the visibility, influence, and integration of Chinese scholarship into global knowledge networks—supporting both academic advancement and policy relevance.

Thematic Directions and Cultural Divergence: Chinese- and English-language studies demonstrate distinct thematic and methodological tendencies. Chinese research often focuses on healing environments and physiological monitoring-such as EEG and eye-tracking-rooted in embodied cognition. English-language research places greater emphasis on stress recovery and public policy evaluation, frequently using VR to explore health-related outcomes in urban settings. These differences reflect underlying variations in policy agendas and academic traditions. China's rapid urban transformation has generated demand for tools that capture embodied and sensory experiences. In contrast, Western studies align with longer-standing interests in evidence-based public health and environmental psychology. Future research should aim to bridge these complementary perspectives. By combining the technological precision of Chinese sensor-based studies with the policy-driven and theoretically grounded frameworks found in Western research, scholars can co-develop more holistic, interdisciplinary, and human-centered urban design methodologies.

Theoretical Contributions: This study synthesizes the mechanism linking built environments and pedestrian emotions into a three-stage framework: sensory stimulation, cognitive appraisal, and affective response. This conceptual model provides a useful lens for interpreting emotional experiences in urban space. Additionally, we identified several spatial intervention strategies enabled by VR technology—including the quantitative adjustment of street elements, iterative spatial form optimization, and the emotional translation of cultural symbols. These findings advance the paradigm of evidence-based design by integrating psychological responses into design evaluation. Importantly, our study supports a broader paradigm shift: from engineering-oriented planning to human-centered, emotion-aware design and policy. This shift has far-reaching implications for how urban environments are imagined, evaluated, and governed.

Technological Applications and Future Opportunities: The review also highlights emerging technological applications and future research priorities. First, developing cross-platform data standardization protocols and dynamic mapping models between virtual and real-word environments will improve the ecological validity of experimental data. Second, cross-cultural studies are essential for understanding how local context shapes emotional perception. Third, integrating extended reality (XR) with urban digital twin systems offers potential for real-time emotional feedback to inform design decisions. Finally, ethical standards must be established for immersive research, including protections for

privacy, cognitive well-being, and data transparency. These technological pathways offer a foundation for more adaptive, responsive, and emotionally intelligent urban systems.

This study provides methodological support for multimodal data-driven healthy city design, innovation in spatial intervention techniques, and the formulation of future smart city renewal policies. It contributes to advancing urban renewal models toward a human-centered orientation. Future work should continue to explore technological reliability verification, cross-cultural theoretical integration, and mechanisms for practical implementation.

Practical Implications and Limitations: By integrating bibliometric analysis, cultural comparison, and spatial design theory, this study contributes both conceptual clarity and practical guidance. It provides a methodological foundation for using VR in data-driven healthy city design, spatial intervention innovation, and policy formulation. The proposed framework supports the transformation of urban renewal practices toward more inclusive and emotionally responsive models.

Nonetheless, the limitations of VR-based research must be acknowledged. While VR enables precise control and immersive simulation, it cannot fully reproduce the multisensory, embodied, and social dynamics of real urban environments. It also remains challenging to capture the perceptions of residents with diverse age groups or physical abilities within standardized virtual scenarios.

To address these limitations, we advocate for a hybrid evaluation framework. In this approach, VR is used in the early design phase to test spatial hypotheses, followed by real-world implementation and post-occupancy evaluation. Feedback should be gathered through sociological surveys, video-based behavior tracking, and audio-recorded verbal responses, allowing users to articulate both the convenience and limitations of designed spaces. These insights can then guide iterative refinement and re-testing, forming a continuous feedback loop between simulation and lived experience. This blended methodology strengthens both the scientific validity and practical impact of urban design, aligning virtual modeling with real-world human needs.

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