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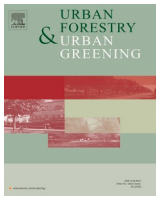

Original article

Subjective perception or the physical environment: Which matters more for public area visitation thresholds across different COVID-19 pandemic stages?

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ABSTRACT

Urban visiting patterns refer to how people visit, use, and move through urban spaces like parks, business districts, and public plazas. Green spaces and businesses significantly influence visitation patterns in urban areas, as key indicators of urban vitality. The COVID-19 pandemic reshaped these dynamic patterns. This research examines visitation patterns in Las Vegas from 2019 to 2023, focusing on green spaces and businesses in relation to environment and human perceptions during the pandemic. We integrated GPS data, Google reviews, and street-view images, applying natural language processing (NLP) and machine learning to analyze sentiment, comment topics, and environmental features, with partial dependence plots (PDP) exploring correlations with visitation patterns. Results reveal both park and business visitation patterns were significantly altered by the COVID-19 pandemic, impacting behaviors and emotional needs. There are significant differences in the usage and perception of parks and commercial areas. Parks, with their natural landscapes, offer restorative and emotional experiences, while business environments cater to functional and service-based needs. Environmental factors better explain park visitation, while sentiment and comment topics better explain business visits. Green spaces demonstrate greater crisis resilience than business areas through their environmental benefits and adaptability. Pre-pandemic, parks were valued primarily for entertainment facilities and activities; post-pandemic, natural elements and infrastructure gained importance. These findings emphasize the need for urban design that integrates green spaces which provide opportunities for physical activity, social interaction, and mental restoration to better withstand future challenges. Planners and policymakers should prioritize green spaces for both their physical and emotional benefits.

1. Introduction

Visitation patterns refer to the identifiable trends in how people access, use, and navigate various Points of Interest (POIs), which include parks, business facilities, transportation hubs, civic spaces, and more (Betancourt et al., 2023). POIs are specific locations within a city, such as restaurants, parks, gyms, or museums, characterized by their functionality and significance in supporting various human activities (Q. Li

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et al., 2021). The study of visitation patterns at POIs provides critical insights into urban vitality and quality of life, as these patterns reflect changes in a society's economy, culture, and lifestyle, while also revealing their interrelationships (Song et al., 2020). Visiting patterns of POIs facilitates urban planners in designing more livable and sustainable urban environments (Huai et al., 2022).

The COVID-19 pandemic has caused shifts in POI visitation patterns, marked by a significant decline in business area visits, and park visitation trends show notable geographic and temporal variations. Business areas were particularly affected, with Li et al. (2021) identifying notable decreases across several POI-associated business categories. In contrast, some regions experienced increased park usage, outdoor spaces like parks gained popularity as safe, open-air environments (Lu and Song, 2024); Rice and Pan (2021) reported a 20.2 % increase in park visitation at the county level when comparing the baseline period to the pandemic period. However, some municipalities imposed strict park closures or restrictions, especially during the early outbreak stages, to curb viral transmission, thus reducing or fluctuating park use in certain regions (Csomós et al., 2023; Volenec et al., 2021). The pandemic's impact on park visitation manifested heterogeneously across policy frameworks globally.

Business areas, as centers of economic activity, enhance urban vitality through social interaction, consumption, employment opportunities, and various economic activities (Li et al., 2021). Using Dewey's classification system, POIs within business areas are categorized under "Commercial Services," which encompass establishments dedicated to retail, hospitality, and personal services, serving essential hubs for daily economic and social exchanges.

On the other hand, parks, with their natural elements and tranquil environments, provide opportunities for people to connect with nature, engage in outdoor recreation, and participate in social interaction (Chiesura, 2004; Cohen et al., 2007). Parks fall under Dewey's classification as "Public and Recreational Spaces," encompassing national parks, urban greenspaces, playgrounds, and community gardens. This categorization reflects the varied functions of parks in providing nature access and facilitating leisure activities. Studies demonstrate that parks foster physical activity, enhance mental health, and increase life satisfaction, with accessibility, size, and facility quality directly influencing visitation patterns (Pfeiffer et al., 2020; Tang et al., 2024; Wood et al., 2017). Urban parks not only serve as venues for recreation and leisure but also enhance residents' physical and mental health through their natural landscapes and ecosystem services (Huai et al., 2022).During the COVID-19 pandemic, parks became vital resources for maintaining public well-being, offering safe environments for outdoor activities and mental restoration. The availability of quality data and timely insights regarding park use during the pandemic has been critical for effective park management and for providing indicators of public health(Rice and Pan, 2021).

Building upon these perspectives, the present study examines the changes in visitation patterns of urban parks and business areas during the COVID-19 pandemic, covering the period from 2019 to 2023. The pandemic-era visitation patterns illuminate considerations for integrated urban planning and public health approaches to strengthen metropolitan resilience against future crises.

2. Literature review and framework

2.1. Theoretical foundation

Existing literature provides a theoretical and methodological foundation for this study. First, classic research by Jacobs (1961) and Gehl (1971) on the vitality of public spaces and residents' behavioral interactions offers a solid theoretical base for understanding how urban spaces influence social interaction and psychological well-being through design. Their established connection between spatial configuration and social patterns enables our comparative analysis of park and businesses space visitation during the pandemic. Additionally, works by Rapoport (1977) and Kaplan and Kaplan (1989) in environmental psychology demonstrate the restorative effects of natural environments on mental health, providing support for this study's discussion of parks as restorative spaces. Recent studies (e.g., Bi, 2024; Xie et al., 2020) demonstrate significant disparities in green space versus commercial area effects on resident psychological and behavioral responses, providing essential context for comparing visitation patterns during the pandemic. On the methodological side, recent studies have widely adopted ML and non-linear models to analyze the complex relationships between environmental features and human behavior (Cao and Tao, 2023; Wu et al., 2023) This research draws on these methods and further integrates richer data sources, such as Google reviews and SVIs, to comprehensively explore the interaction between environmental features, sentiment feedback, and visitation patterns. By applying these methods, this study not only identifies the non-linear effects of environmental features on behavioral patterns but also reveals how these effects evolve under external shocks, such as the COVID-19 pandemic.

2.2. The impact of environmental features on human perception

The influence of environmental characteristics on human perception and preferences is a key perspective in environmental psychology and behavioral studies. In recent years, as research on cultural ecosystem services has deepened, scholars have increasingly focused on the intangible contributions of natural environments to human well-being, such as mental health, emotional fulfillment, and aesthetic experiences. Urban green spaces deliver diverse ecosystem services that mitigate illness effects while enhancing quality of life and overall health outcomes, as documented by numerous researchers (Cai et al., 2024; Xie et al., 2020). Research further shows that the presence of urban green spaces and water bodies can significantly enhance residents' well-being and quality of life (Costanza et al., 2017; Riechers et al., 2016). Previous studies suggest that environmental characteristics not only determine the physical functions of a space but also shape residents' behavioral patterns through aesthetic, cultural, and psychological experiences (Han et al., 2022; Jens and Gregg, 2021). Additionally, Bi (2024) demonstrated that landscape diversity, naturalness, and artificial design harmony directly influence residents' cultural ecosystem service perceptions, with significant variations between park and commercial contexts.

2.3. Impact of COVID-19 on urban space and mobility

The COVID-19 pandemic profoundly disrupted mobility and visiting patterns. Although the benefits of natural environments and social interaction for public health are widely recognized (Kleinschroth and Kowarik, 2020; Xie et al., 2020), after the World Health Organization declared COVID-19 a global pandemic, governments worldwide implemented unprecedented measures to slow the spread of the virus (Kleinschroth and Kowarik, 2020; Li et al., 2024). These measures restricted individual mobility and disrupted daily life, including travel behavior, social activities, and work-related tasks (Li et al., 2024; Song et al., 2023), reducing residents' physical and mental well-being (Xie et al., 2020).

Against this backdrop, visiting patterns in public spaces underwent significant changes. Kleinschroth and Kowarik (2020) observed that despite initial openness of public parks in European cities, social distancing enforcement challenges prompted varying access restrictions. They further contended that COVID-19 offered an urban planning opportunity by highlighting green spaces' critical role in urban quality of life enhancement.

Additionally, Y. Song et al. (2023) examined campus visitation patterns pre/post-pandemic, finding significant declines particularly at dining and recreational facilities, indicating decreased campus dependency among nearby residents. Xie et al. (2020) emphasized urban

parks' importance during the pandemic, finding that while many felt isolated and health-conscious, park visits improved health and fulfilled social needs.

Restoring urban vitality in the post-pandemic era has also become a research priority. S. Li et al. (2024) examined how lockdowns impacted urban vitality recovery, finding that Shenzhen's vitality only rebounded to 86 % of 2019 levels, with some areas still declining. The recovery exhibited spatial variations, influenced by factors like population density, traffic flow, and urban layout.

The shifts in visiting patterns and spatial use during COVID-19 pandemic also offered new insights into understanding the relationship between urban spatial planning, public health, and sustainable development. While studies have explored factors like urban density, traffic, and morphology (Li et al., 2024), more research is need on visiting patterns' changes, comparison, and recovery across different types of urban spaces, as well as on the combined effects of environmental factors, human perceptions, and emotions.

2.4. Application of data science and non-linear methods in urban visitation studies

The rapid development of data science has introduced a new approach to studying urban visiting patterns (Lee, 2023). Researchers increasingly use new data sources, such as social media and location data, to analyze urban visiting patterns (Chen et al., 2024; X. Li et al., 2021; Song and Schuett, 2023). In contrast to traditional survey methods, social media's user-generated content provides researchers with real-time, extensive datasets (including comments, photos, geolocation, and tags) that can capture residents' perceptions and preferences of urban environments (Ma et al., 2023). This approach offers multidimensional data revealing emotions, attitudes, and preferences for understanding public perception and behavior.

Huai et al. (2022) and L. Li et al. (2023) analyzed social media imagery and check-in data to identify resident behavioral patterns in parks and determine how landscape features affect visitation intensity and preferences. Ma et al. (2023) combined social media comments and images with eye-tracking technology and sentiment analysis to assess people's satisfaction with and attention to different types of urban space elements, offering recommendations for improvement. Similarly, C. Yang et al. (2022) and Y. Yang et al. (2022) utilized image data from the Flickr platform to visualize the intensity and distribution of urban space usage, providing scientific evidence for urban planning. These studies illustrate that social media data can not only uncover the functionality of environments but also quantify people's emotional responses and aesthetic evaluations.

Although numerous studies have explored the impact of urban spaces, particularly urban parks, on residents' behavior, most existing research has focused on the application of linear models. These studies primarily rely on traditional statistical methods, such as regression analysis, to reveal the linear relationship between environmental factors and behavioral patterns (Bi, 2024; Huai et al., 2022). However, real urban environments and human behavior are influenced by multiple factors simultaneously (Ardic et al., 2020; Zhang et al., 2021), with potential interactions, nonlinear effects, and lag effects between variables. Simple linear relationships struggle to capture the complex, nonlinear interactions between the environment and human perception. For example, certain key environmental elements, such as green space or the layout of business areas, may influence human behavior choices in a nonlinear manner (Bi, 2024). Particularly when faced with external shocks, such as the COVID-19 pandemic, linear models and traditional predictive methods are insufficient for reflecting real-word complexities (Owuor and Hochmair, 2023). To address this issue, researchers have started to introduce nonlinear models and machine learning (ML) methods, such as generalized linear models or quadratic regression, to explore these nonlinear relationships (Cao and Tao, 2023). F. Wu et al. (2023) used random forests combined with street view images (SVI) to assess the nonlinear impact of micro-level streetscape features on active school commuting. Ding et al. (2018) applied a gradient boosting decision tree model to study the subtle nonlinear effects of distance to different levels of centers in Oslo, Norway, on driving distances. Similarly, Doan et al. (2025) tested the performance of various models and ultimately adopted Extreme Gradient Boosting combined with SVIs to examine the nonlinear and threshold effects of the built environment, road vehicles, and air pollution on urban vitality. Tao and Cao (2023) used a gradient boosting decision tree model to analyze the nonlinear effects of regional and local built environment characteristics on distances traveled using different modes of transportation. However, the complex nonlinear models used by Doan et al. (2025) often function like a 'black box,' making their internal mechanisms difficult to interpret. This lack of transparency can limit their applicability in practical urban planning and policymaking.

2.5. Addressing gaps in existing research

Despite the numerous studies exploring the impact of the COVID-19 pandemic on urban space usage and the interaction between environmental features and human perception, several critical research gaps remain. First, existing research predominantly examines single space types without systematic comparison, limiting understanding of diverse urban environments' influence on behavior and perception during the pandemic (Bi, 2024; Huai et al., 2022). Second, most studies rely on linear models that fail to capture the complex, non-linear relationships between environmental features and visitation patterns. Urban environments and human behavior are shaped by multiple interacting factors, which linear analyses cannot adequately reveal, particularly when external shocks like the COVID-19 pandemic are involved (Cao and Tao, 2023). Furthermore, while the use of data science methods has provided more comprehensive datasets, there is still a gap in how to leverage unstructured data, such as social media reviews, to reveal the complex relationships between environmental characteristics and behavioral patterns. The potential of such data has not been fully exploited, especially in terms of integrating sentiment analysis and environmental features to explain visitation patterns (Ma et al., 2023).

This study aims to fill these gaps by using machine learning techniques, integrating multiple data sources (including GPS visitation data, Google reviews, and Streetscape Visual Indices, SVIs), and systematically comparing visitation patterns between parks and commercial areas. By exploring the non-linear impacts of environmental features and human perceptions, as well as analyzing the moderating role of external shocks (such as public health events like COVID-19), this research provides new theoretical and empirical insights into how different types of urban spaces influence residents' behaviors. Although the pandemic offers a unique case for understanding short-term behavioral changes, this study primarily focuses on identifying the broader and more persistent mechanisms through which urban environments and perceived qualities shape people's spatial behaviors.

Using Las Vegas as a case study, this research employs a combination of topic modeling techniques integrated with large language models (LLMs) and computer vision methods to systematically extract and quantify environmental characteristics. Furthermore, by incorporating interpretable ML approaches to examine threshold and non-linear relationships, the study aims to reveal complex dynamics between environmental features, human perceptions, and visitation behaviors. The ultimate goal is to provide urban planners and policymakers with concrete, actionable data and evidence-based insights to inform the long-term design and management of urban spaces that better align with residents' needs and preferences. Accordingly, this study proposes the following three core research questions:

1) What potential topic does people focus on when visiting commercial areas and parks?

2) How do these perception topics and environmental factors respectively influence urban visiting patterns, and which one has a stronger explanatory power for these patterns?
3) How can the nonlinear relationship and detailed threshold effects between environmental factors and review topic on visiting patterns be explained? How have external shocks, such as the pandemic, influenced these effects?

3. Methods

This study investigates visitation patterns in urban parks and commercial spaces in Las Vegas using a multi-source data approach. We employ advanced models and machine learning techniques to explore the relationships among review topics, sentiment, environmental features, and visitation behavior, with a specific focus on the impacts of the COVID-19 pandemic

3.1. Study area

Las Vegas area is situated in the southern part of the United States of America's Nevada state on the edge of the Mojave Desert (Fig. 1). It is the most populous city in the state with Las Vegas Valley's metropolitan area that sustains more than two million individuals. Renowned as the "Entertainment Capital of the World," Las Vegas attracts tens of millions of visitors annually, with the economy relying heavily on hospitality, gaming, and convention business. The city boasts a population base made up of long-term residents and workers who migrate for jobs in the hospitality sector. The climatic characteristics of the area are hot summers and mild winters, which influence individuals' connections to urban spaces, particularly parks and outdoor recreation areas. The COVID-19 pandemic significantly affected Las Vegas, resulting in interruptions to tourism and mobility flows. Restrictions imposed by the government resulted in the short-term shutdown of large resorts and entertainment centers, thus creating a novel chance to examine visitation behavior during a time of crisis. This research employs Las Vegas as a case study to explore how environmental factors, review themes, and human attitudes influence visitation flows in commercial and recreational settings during the pandemic era. Fig. 1 illustrates the dispersal of significant commercial and recreational zones examined in this research.

3.2. Analytical framework

As shown in Fig. 2, the analytical framework integrates social media reviews with built environment features extracted from street-view images to gain insights into urban visitation patterns. The research employs multiple data sources, including the Dewey Monthly Pattern GPS dataset, Google Maps reviews (2018–2023), and Google Street View imagery. For data analysis, the study utilizes the BERT model for extracting and analyzing key themes and sentiments from review data. Environmental features are quantified using the PSPNet computer vision model applied to Google Street View images. To explore the relationships between variables, a random forest regression model is employed, along with Partial Dependence Plots (PDPs), to investigate non-linear and threshold effects. All data was mapped to corresponding years based on timestamps, ensuring within the same time range to reduce potential statistical bias.

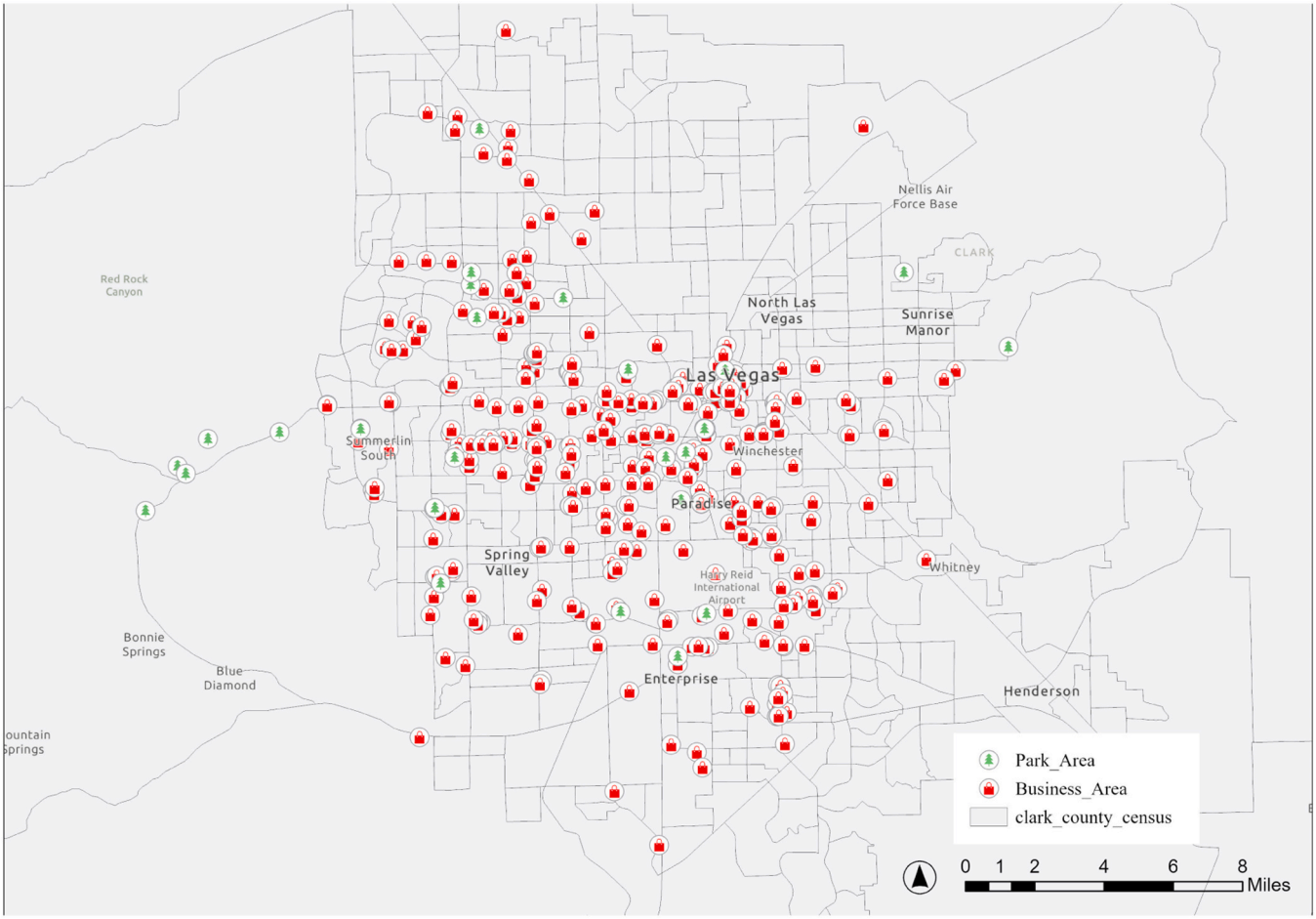

Fig. 1. Las Vegas Area.

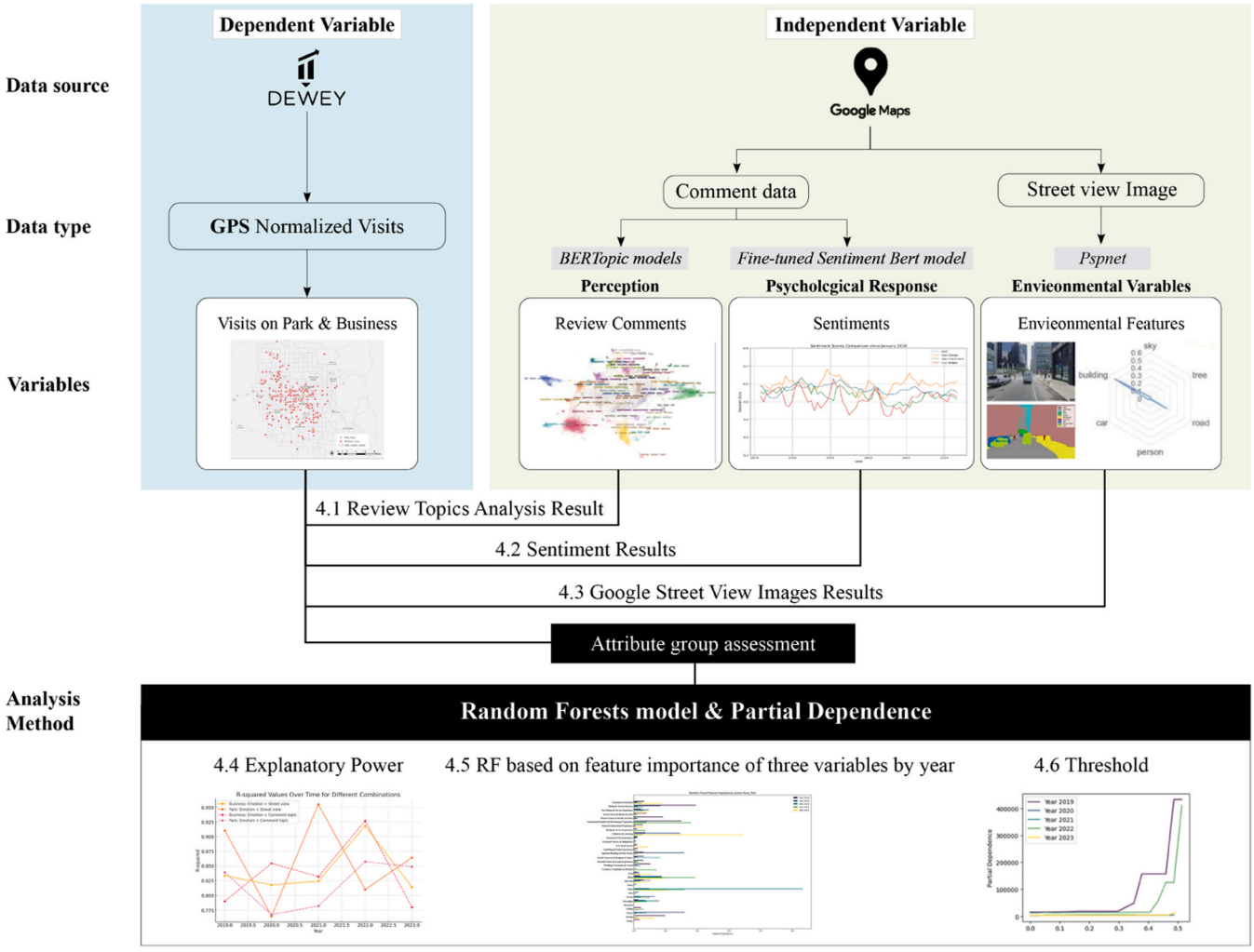

Fig. 2. Research workflow.

3.3. Dependent variable: visitation data and POIs

The primary dependent variable in this research is *Normalized Visits by Total Visits*, which captures visitation patterns across various points of interest (POIs) in parks and commercial areas. The visitation data, sourced from the Dewey Monthly Pattern GPS dataset (2018–2023) which is based on millions of anonymous visits by mobile phone users across the US. It provides reliable location information of POIs in downtown Las Vegas, as well as information on visitor counts, average dwell time, and travel distance for each POI. We measured POI popularity over time using "Normalized Visits by Total Visits," which adjusts for city-wide visit fluctuations, allowing for comparative popularity analysis across periods. POIs were categorized as “Parks” or “Commercial Services” based on Dewey’s classification. Finally, our analysis includes 82 parks and 771 businesses areas POI.

3.4. Independent variable: review topic, sentiment and environmental features

The independent variables include review topics, sentiment, and environmental features. Google review data were analyzed using the BERTopic model, which extracted and clustered key themes from visitor feedback.

3.4.1. Review topics

Many POIs had limited feedback, often with fewer than fifty reviews or predominantly short, low-context comments (e.g., one-word reviews like ’Nice’). Therefore, we adopted a data-weighting approach, applying a logistic function to scale review frequencies logarithmically, which allowed retention of valuable insights from locations with sparse data. Reviews shorter than 15 words were excluded to maintain analytical validity.

Then, by using the BERTopic model to analysis google review for each POI, we identified the most prevalent topics and used hierarchical clustering to streamline these into 20 topics for both business and park reviews. For model architecture, training and analysis processing details can be referred to in Appendix A

3.4.2. Review sentiment

For Human Perception Sentiment, we used Google review data combined with the Fine-tuned Sentiment BERT model from Hugging Face for sentiment analysis and ranging from −1 (extremely negative) to 1 (extremely positive). We calculate an annual sentiment score for each place based on each years google review. The detail process is shown in Appendix B

3.4.3. Google street view image environmental features

For the environmental features, we used Street View Images (SVIs). Our image analysis methodology prioritized spatial precision and environmental context. Previous studies have shown that features such as green spaces and spatial openness can influence human mobility decisions (Chen et al., 2024; Dong, 2023; Song and Schuett, 2023). Since

these images are captured along streets, they primarily depict street entrances. To address this limitation, we selected images closest to the POI to ensure accurate representation. Using the geographic coordinates of each POI, we retrieved the corresponding SVIs and performed image segmentation with the PSPNet model and ADE20K dataset (Fig. 3), which labels approximately 150 object categories for pixel-level semantic segmentation. This allowed us to segment each image and calculate the proportions of various elements within the image. The details about how to ensure consistent visual representation across locations can see in Appendix C

3.4.4. Random forests model and Partial Dependence Plots (PDPs)

We used a random forest model to explore the relationships between variables and account for potential nonlinear interactions (Doan et al., 2025). This ensemble learning method constructs multiple decision trees and aggregates their results, effectively capturing complex nonlinear relationships. We selected this model for its capacity to handle high-dimensional data and intricate variable interactions.

To further examine the influence of each independent variable on the target variable (e.g., visitation), we used PDPs. PDPs visually demonstrate how changes in a single independent variable affect the target variable while controlling for others. They help identify key inflection points or thresholds where the variable's impact is significant within a certain range but diminishes or changes beyond it. Analyzing PDPs validates nonlinear relationships and aids in model optimization and decision-making (Tao and Cao, 2023; Wu et al., 2023). This approach provides deeper insights into variable interactions.

4. Results

4.1. Review topics analysis results – topic weighting differences between commercial spaces and parks

The analysis of Google review data using the BERTopic model revealed distinct themes that characterize visitor perceptions of parks and commercial spaces. A total of 20 primary topics were identified for each type of environment based on their waiting. (Fig. 4). The results reveal significant differences between the two, while also highlighting commonalities.

Park-related topics primarily focus on natural landscapes, outdoor activities, and recreation, with keywords like 'trail,' 'hike,' 'view,' and 'beautiful' reflecting visitors' preferences for nature (Appendix D). Weighting in topics of Park: Explain Keywords such as 'kids,' 'play,' and 'wedding' emphasize parks as spaces for family recreation and social gatherings. In contrast, commercial spaces emphasize professional services, technical support, and customer experience, with high-weight keywords like 'professional,' 'service,' 'legal,' 'software,' and 'trading' highlighting their strength in offering specialized services (Appendix E). Keywords such as 'customer,' 'recommendation,' and 'satisfaction' stress the importance of customer satisfaction and reputation.

Despite their differences, both environments emphasize service quality, evident in keywords such as 'service,' 'great,' and 'experience.' Health and fitness are also shared focal points, with keywords like 'fitness' and 'class' indicating a commitment to promoting a healthy lifestyle. Parks place more emphasis on nature and emotional experiences, reflected in keywords like 'peaceful,' 'fun,' and 'relaxing,' while commercial spaces focus on professionalism and technical expertise, using terms like 'data,' 'security,' and 'efficient' to underscore their specialized services.

Park reviews highlight emotional experiences and interactions with nature, while commercial reviews focus on specialized services, emphasizing customer satisfaction and efficiency. Both environments recognize the importance of high-quality service in enhancing user experience.

4.2. Sentiment results – differences between commercial spaces and parks

Parks exhibited a clear upward trend in sentiment scores, starting from 0.523 in 2019 and peaking at 0.632 in 2021 before slightly stabilizing in subsequent years (0.624 in 2022 and 0.568 in 2023). This trend reflects the increased reliance on parks during the COVID-19 pandemic, as restrictions on travel and indoor gatherings made outdoor spaces a preferred option for recreation and socialization.

In contrast, commercial areas displayed relatively stable sentiment scores over the same period, ranging from 0.625 in 2019 to a slight peak of 0.661 in 2020. This was followed by a mild decline to 0.631 in 2022 but showed a recovery to 0.651 in 2023. This rebound suggests a gradual return to normalcy as pandemic-related restrictions eased, allowing commercial areas to regain visitor confidence and engagement Fig. 5.

4.3. Google street view images results – differences between commercial spaces and parks

The analysis of street-level environmental features using the PSPNet model provides insights into physical characteristics. Parks demonstrate significantly higher weights for trees (0.0504) and mountains (0.0514). However, the weight for plants in parks (0.0106) is slightly lower than in commercial areas (0.0196), potentially due to the increasing use of greenery in commercial settings to optimize the environment and attract more visitors. Additionally, road coverage in commercial areas (0.1901) is significantly higher than in parks (0.1074), reflecting the dense road networks typically required in commercial zones. The ceiling value in parks (0.1116) is markedly higher than in commercial environments (0.0073), suggesting that parks have a greater proportion of overhead structures (e.g., pavilions) in outdoor settings, whereas commercial areas are characterized by a predominance of open sky Fig. 6.

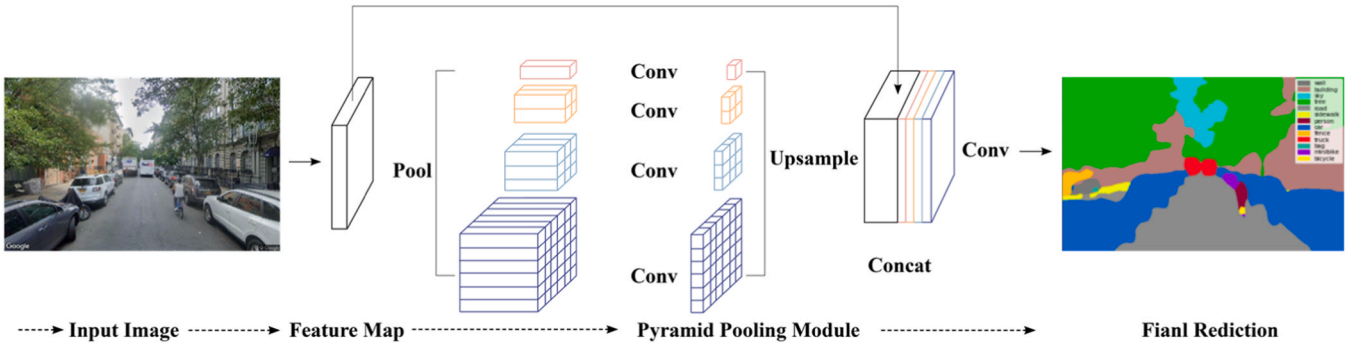

Fig. 3. Schematic diagram of PSPNet model.

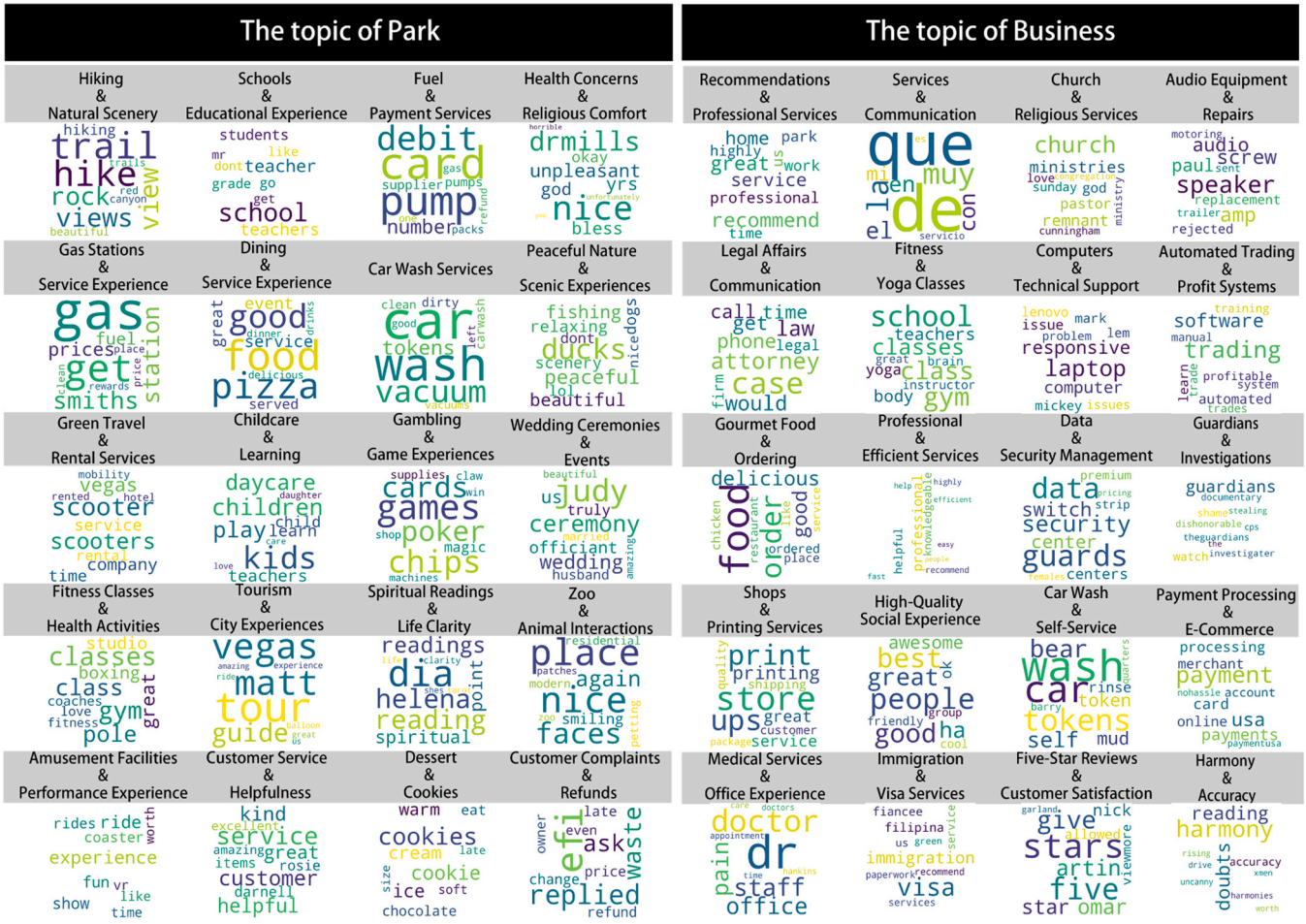

Fig. 4. Word cloud of review topic for parks and commercial environments.

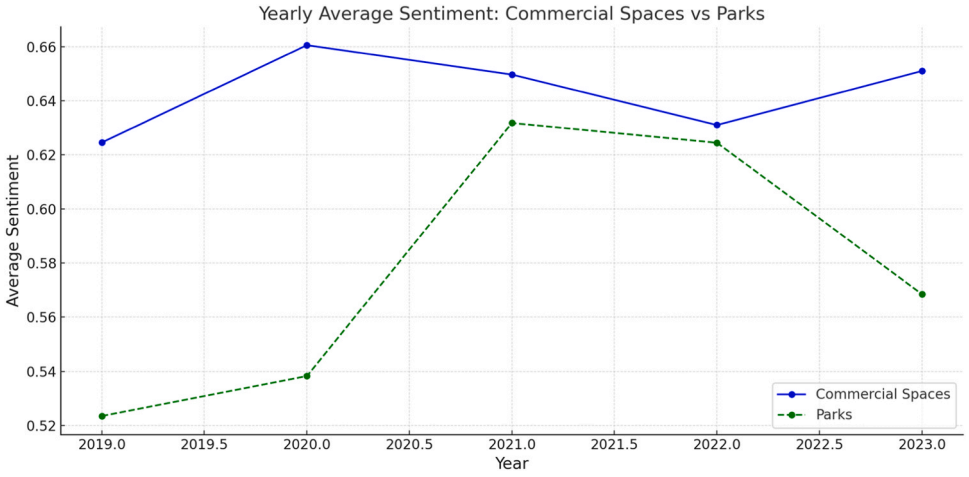

Fig. 5. Yearly average sentiment.

4.4. Comparison of explanatory power – review topics v.s. environmental models

The Random Forest regression analysis revealed important interrelationships among review topics, sentiment, and environmental features. We used random forest models to compare the explanatory performance of the Sentiment + Review Topics, Sentiment + Street View, and Street View + Review Topic models in both commercial and park environments. The results show that, in most years, street view data provided stronger explanatory power for park visitation patterns than review topics, whereas all three models showed comparable performance in commercial environments (see Appendix F to K for details). Notably, in 2022, the Sentiment + Review Topics model significantly outperformed the other models in commercial settings, suggesting an increased influence of online reviews on commercial visitation that year (see Appendix L for details).

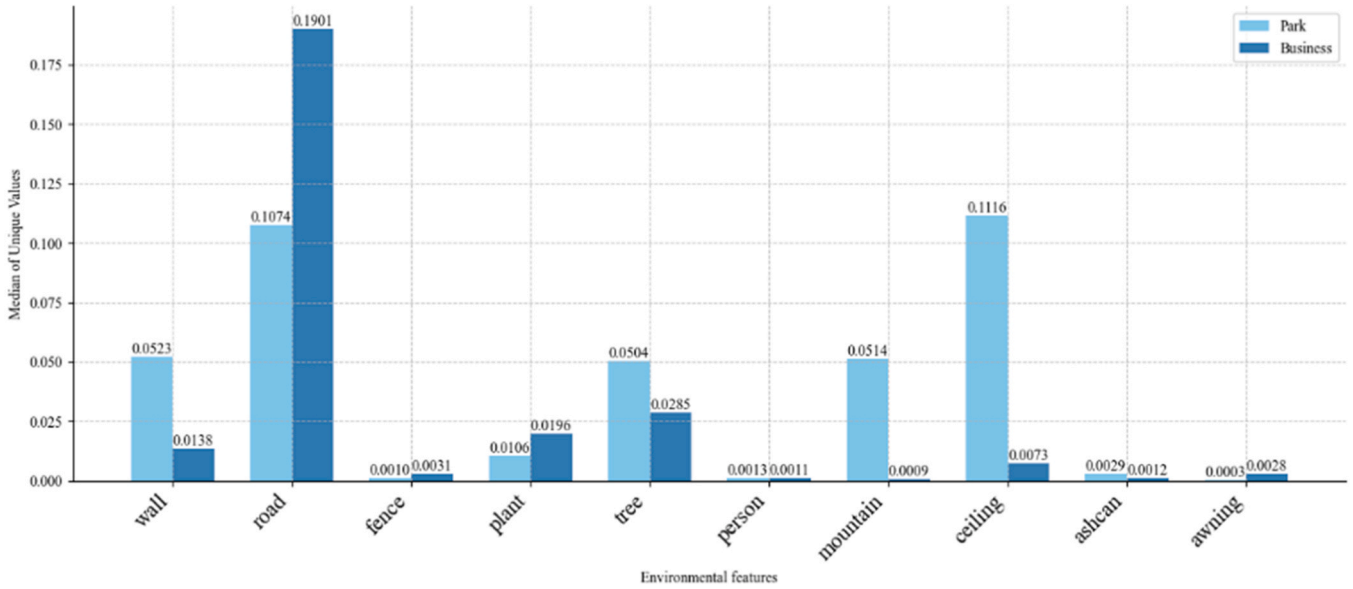

Fig. 6. Median of Unique Values for Selected Environment Elements.

The explanatory power of models fluctuated annually across both environments (Fig. 7), reflecting behavioral shifts during pandemic conditions, economic recovery periods, and evolving public emotional priorities. During the pandemic, variables such as sentiment, review topics, and street views showed significant shifts in explanatory power. Early on, commercial reviews gained explanatory power while park reviews declined, likely due to a greater reliance on online information for commercial activities. As the pandemic continued, park street view data gained explanatory power, peaking in the later stages and surpassing commercial settings in explaining sentiment. Meanwhile, as in-person commercial activities resumed, reliance on online reviews decreased, leading to a decline in the explanatory power of review topics in both environments. The Street View + Review Topic model consistently demonstrated strong explanatory power in both settings, highlighting the importance of integrating multiple data sources (see Appendix M for details).

4.5. *Yearly analysis of feature importances in random forest models*

The importance of variables in both commercial and park environments shifted before and after the pandemic (Appendix N1 and N2). Prior to the pandemic, visitor behavior was primarily influenced by

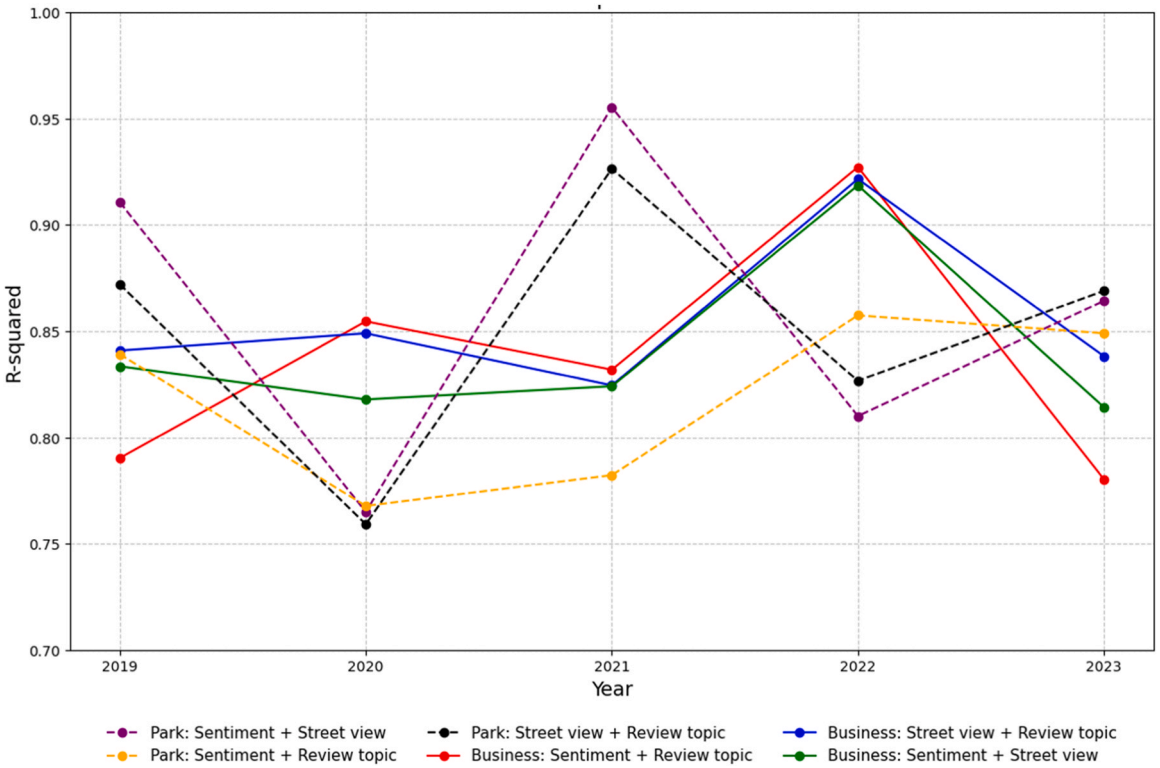

Fig. 7. Explanatory annual variations in different combinations.

human activities and natural elements. Post-pandemic, emotional experiences, natural environments, and specific activity types became much more prominent.

In commercial settings, 'Tree', 'Person', and 'Normalized Sentiment' demonstrated substantial increases in importance, with 'Tree' emerging as the dominant factor post-pandemic. This was accompanied by growing significance of themes related to 'Shops & Printing Services' and 'Services & Communication', reflecting evolving consumer priorities that balanced practical service needs with emotional considerations.

In park environments, the importance of natural landscapes and recreational activities grew substantially, with 'Plant,' 'Hiking & Natural Scenery,' and 'Childcare & Learning' emerging as key variables in the later pandemic stages. Notably, 'Plant' became the most influential variable during the mid-pandemic period, highlighting the strong demand for greenery and outdoor environments.

Overall, in the post-pandemic period, the interaction between emotional experiences and natural elements became increasingly important in commercial environments, while in parks, natural landscapes, infrastructure, and recreational activities continued to dominate behavioral patterns. This suggests the pandemic had a markedly different impact on visitor behavior in these two settings (see Appendix O for details).

4.6. Visitation analysis of nonlinear effects in commercial and park contexts

4.6.1. Nonlinear outcomes of review topics and visiting patterns

Regarding review topics (Appendix P) in parks, natural and service-oriented experiences such as 'Hiking & Natural Scenery' and 'Green Travel & Rental Services' were significantly affected during the pandemic, but demand recovered by 2023 as visitor numbers stabilized (Fig. 8a). Health-related themes like 'Fitness Classes & Health Activities' also indicate an increased public focus on health in the post-pandemic period (see Appendix Q for details).

In commercial environments, service-oriented themes such as 'Recommendations & Professional Services' and 'Medical Services & Office Experience' showed strong recovery during the pandemic, reflecting a rise in demand for professional and medical services (Fig. 8b). However, the recovery of entertainment and social experiences was slower, with themes like 'High-Quality Social Experience' not fully returning to pre-pandemic levels, highlighting the long-term impact of the pandemic on social activities.

4.6.2. Nonlinear outcomes of sentiment and visiting patterns

In terms of review topics, Normalized Sentiment in parks (Fig. 9) had a negative impact on visitation in both 2019 and 2023, with the negative effect becoming particularly pronounced after the pandemic fully ended in 2023. As the index increased, visitation showed a sharp decline in a gradient manner, leveling off around 45,000 visits when the sentiment score reached 0.2. This indicates that as the pandemic subsided, the impact of Normalized Sentiment on park visitation returned to a relatively strong level. Similarly, the Normalized Sentiment variable in commercial environments exhibited a similar fluctuation trend, but with an even stronger effect. The difference lies in the fact that, in 2023, its impact on vitality in commercial environments approached zero again. This suggests that during the early stages of post-pandemic recovery, people had an increased need for outdoor activities, with heightened attention to negative reviews. However, once conditions returned to normal, sentiment was no longer a major factor influencing vitality in commercial environments.

4.6.3. Random Forest Model Nonlinear outcomes of environmental factors and visiting patterns

Using a random forest model and PDP, we found that the impact of natural landscapes and infrastructure on visitation in parks and commercial environments shifted significantly before and after the pandemic (see Appendix R for details). During the pandemic, the importance of natural elements like 'Tree' and 'Plant' in parks increased markedly. As pandemic restrictions eased, visitation rebounded quickly and remained high. In contrast, 'Mountain'(Appendix S) exhibited stable demand with minimal fluctuations post-pandemic (Fig. 10a). In commercial environments, natural elements had less impact on visitation; however, 'Tree' maintained notable influence during the pandemic (Fig. 10b).

For infrastructure, the influence of 'Streetlight' on park visitation rose significantly, particularly during the later stages of the pandemic, reflecting a growing demand for nighttime activities. In commercial environments, infrastructure recovery was slower, with increased demand for 'Wall' and 'Fence' post-pandemic, indicating a heightened focus on spatial separation and security. The impact of 'Ashcan' and 'Ceiling' fluctuated throughout the pandemic, with overall recovery remaining slow. Notably, in park environments, the 'Person' index dropped sharply due to social activity restrictions, but in later stages, it surged, even surpassing pre-pandemic levels, indicating a strong rebound in social activity demand.

4.6.4. Nonlinear impacts of the pandemic (2020–2021) on visiting patterns

The pandemic had a significant nonlinear impact on visiting patterns in both park and commercial environments, causing noticeable fluctuations in environmental variables and review topics. While both environments shared some commonalities, they also exhibited key differences in their responses to the pandemic.

In park environments, natural landscape and social activity variables were heavily affected during the pandemic. Demand for natural landscape features, such as 'Tree' and 'Plant,' dropped sharply during the early pandemic due to social restrictions but rebounded quickly as restrictions eased, highlighting a redefined public reliance on nature and outdoor activities. Additionally, infrastructure variables like 'Streetlight' and 'Sidewalk,' particularly related to nighttime activities, also showed recovery, underscoring the importance of safety and convenience in park visitation.

In contrast, recovery in commercial environments was slower and more prolonged. The pandemic's impact was most evident in social and service-related topics like 'High-Quality Social Experience' and 'Professional Services,' which showed a slow recovery and had not fully returned to pre-pandemic levels by 2023. This indicates lasting changes in public social habits and demands within commercial spaces. Meanwhile, basic services such as 'Medical Services' recovered more swiftly, reflecting heightened public demand for health and safety during the pandemic.

Overall, parks recovered faster, especially in natural landscapes and health-related activities, while social topics in commercial environments, which were more significantly impacted, recovered more slowly, reflecting complex behavioral and psychological shifts.

5. Discussion

The in-depth analysis of Google review and visitation data for downtown Las Vegas highlights differences and shifts in urban visitation patterns between commercial spaces. Commercial areas primarily attract visitors with functionality and service efficiency, while parks emphasize emotional fulfillment and ecological needs. Review topic analysis shows distinct user perceptions for parks and commercial spaces, underscoring the significant influence of urban environments and human cognition on visitation patterns. Additionally, the relationships between environmental factors, review topics, and visitation patterns are complex and nonlinear. External shocks, such as the pandemic, can dynamically alter behaviors and preferences, leading to shifts in how these factors impact visitation over time.

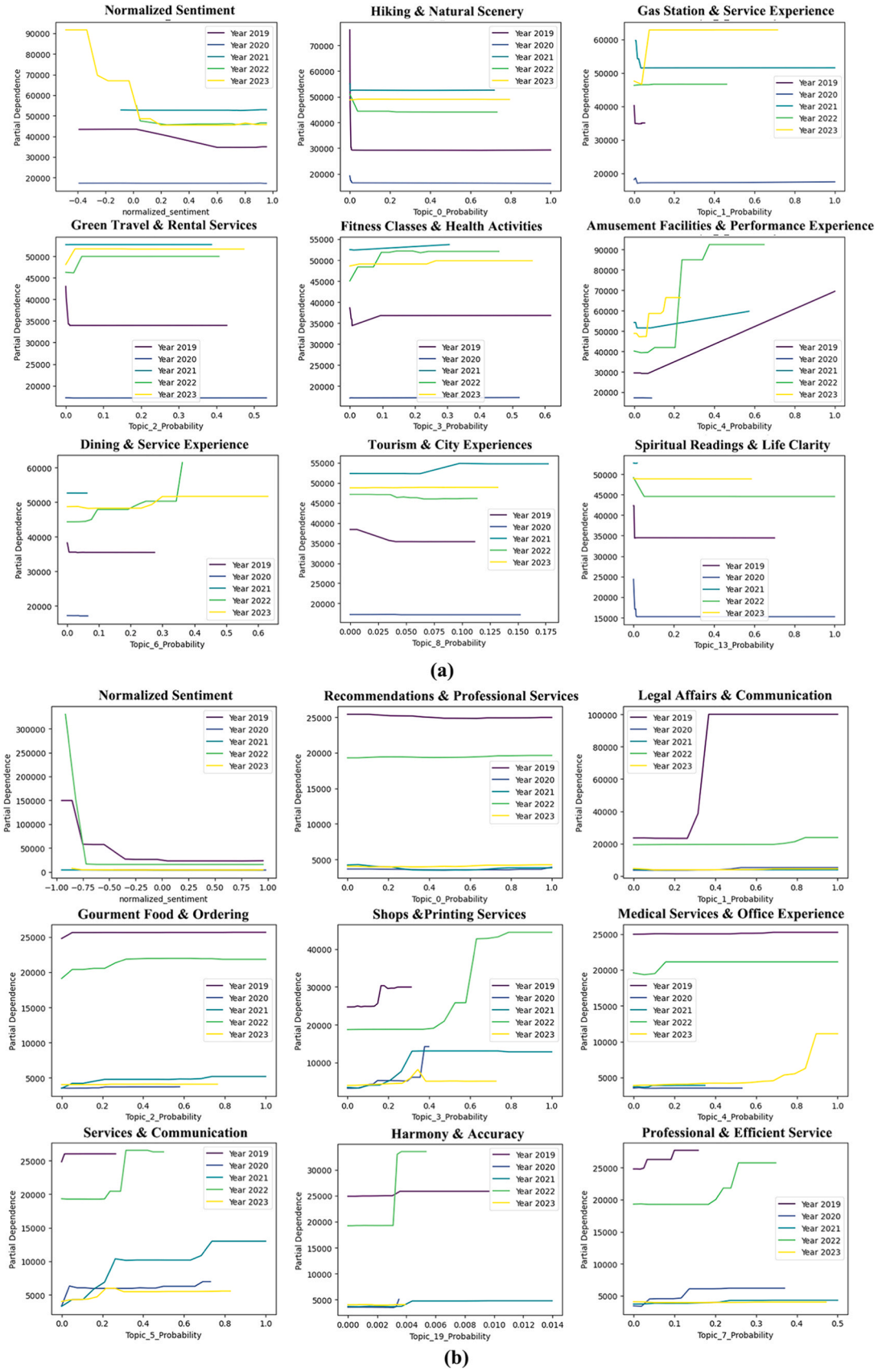

Fig. 8. PDPs of Topic: (a) Park. (b) Commercial environments.

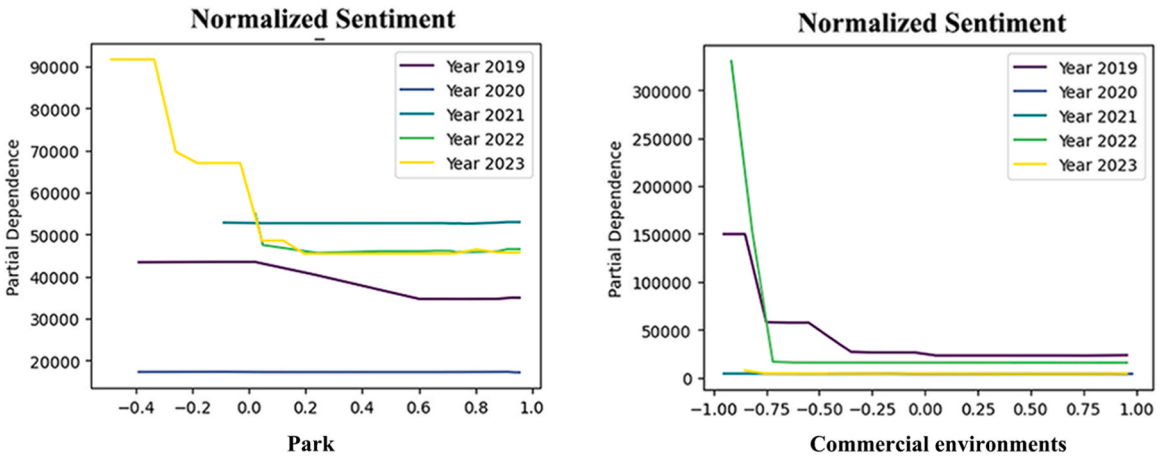

Fig. 9. PDPs of Normalize sentiment: (a) Park. (b) Commercial environments.

5.1. *Identification and analysis of potential topics*

A comparative analysis of review topics between Las Vegas commercial districts and parks reveals significant differences in functional orientation and usage purposes. In reviews of commercial areas, keywords such as 'service,' 'customer,' 'efficiency,' and 'satisfaction' stand out, indicating that consumers primarily emphasize efficient services to meet their immediate needs. Parasuraman et al. (1985) noted that service quality impacts the gap between customer expectations and actual experiences. For example, commercial spaces enhance customer satisfaction by providing streamlined transaction processes and prompt customer support.

Conversely, park reviews place greater emphasis on emotions and experiences, with keywords such as 'relaxation,' 'health,' and 'nature' highlighting the role of natural environments in alleviating stress and restoring psychological and cognitive functions (Ulrich, 1984). Parks are not only spaces for physical activity but also serve as 'oases' in urban life, providing emotional fulfillment and psychological restoration (Kaplan and Kaplan, 1989).

From the perspective of space usage, keywords such as 'transaction,' 'shopping,' and 'service' in commercial district reviews suggest that customer interactions primarily revolve around material needs and functional services (Pine and Gilmore, 2011). Commercial facility design aims to optimize the shopping experience and meet immediate needs. In contrast, keywords such as 'walking,' 'picnic,' and 'outdoor activities' in park reviews reflect the openness and flexibility of park spaces, which support extended leisure activities and cultural experiences (Bourdieu and Bourdieu, 2002). This suggests that park design encourages longer visitor stays and deeper engagement, providing opportunities for rich social and cultural interactions.

In terms of interpersonal interactions, commercial environments place greater emphasis on the service relationship between customers and employees, with service interactions directly influencing customer satisfaction (Oliver, 2010). Keywords such as 'customer,' 'employee,' and 'service' indicate that interactions in commercial environments are centered around the provision and receipt of services. In park environments, keywords such as 'family,' 'friends,' and 'social activities' suggest that parks are not only spaces for individual recreation but also serve as venues for fostering social interaction. Park design prioritizes family and community functions, providing open social spaces that foster social connections and community cohesion (Chen et al., 2024).

Although commercial districts and parks exhibit significant differences in functional orientation and usage purposes, they share commonalities in terms of user experience. In both environments, positive user experiences are crucial. In commercial districts, user experience revolves around expectations of service efficiency and quality. In parks, comfort is derived from the aesthetic value of natural landscapes, the openness of space, and the completeness of facilities (Carmona, 2021). In recent years, urban design policies have increasingly focused on enhancing user satisfaction and spatial experience by improving the physical environment and service quality.

5.2. *The differential influence of topics and environmental factors on visitation patterns*

The results reveal distinct mechanisms driving visitor behavior in parks versus commercial environments. Environmental factors hold greater influence in parks, while review topics are more significant in commercial settings. This suggests that park visitors prioritize natural elements and facility convenience, whereas commercial visitors focus on service and emotional experiences. Visitation patterns in commercial environments largely depend on customers' emotional responses, with fluctuations in emotion reflecting sensitivity to the gap between service quality and expectations (Manyangara et al., 2023; Schweiggart et al., 2025). This underscores the importance of service experiences and the central role of emotions in driving behavior (Mehrabian and Russell, 1974). The increasing influence of service-related review topics indicates a rising demand for service recovery (Pine and Gilmore, 2011). As service processes are optimized and digital technologies implemented, customer experiences improve, directly shaping emotional responses. The interplay between emotions, review topics, and service quality forms a feedback loop that shapes visitor behavior. In contrast, visitation patterns in parks are primarily driven by natural landscapes and infrastructure. Natural landscapes play a crucial role in promoting psychological restoration (Ulrich, 1984). Restorative environments not only provide spaces for physical and mental relaxation but also influence behavior by improving emotional states, indicating that natural environments effectively alleviate mental fatigue and enhance visitors' well-being (Kaplan and Kaplan, 1989). Additionally, infrastructure increases visitors' reliance on parks by improving their sense of safety and convenience. These infrastructures not only offer functional support but also enhance the overall appeal of parks, especially during nighttime activities when visitor demand for infrastructure rises significantly, reflecting the diversity of visitor behavior. Although environmental factors dominate in parks, certain review topics may interact with these factors, amplifying the importance of specific variables in certain years. For instance, visitors' high expectations of natural landscapes generate positive feedback with environmental quality, thereby influencing visitation patterns (Gössling et al., 2021). Similarly, in commercial environments, the interaction between review topics and physical factors such as streetscapes can amplify customers' emotional responses, leading to more complex behavior patterns, which in turn increase visit

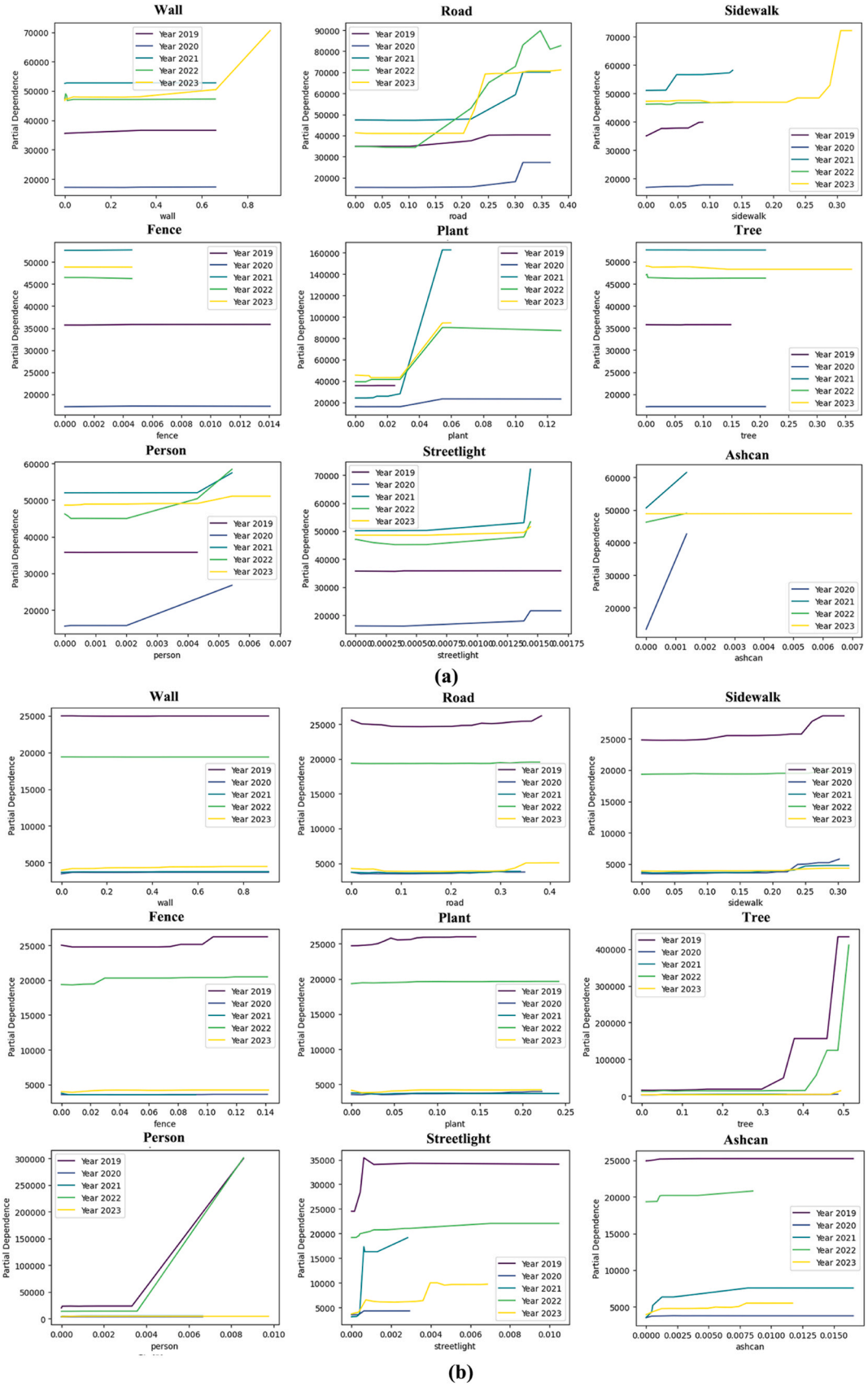

Fig. 10. PDPs of Environment: (a) Park. (b) Commercial environments.

frequency and duration (Bitner, 1992). As a result, streetscape data in commercial environments exhibits strong explanatory power for visitation patterns, aligning with environmental psychology expectations.

5.3. The nonlinear influence of environmental factors, emotions, and review topics on visitation patterns

This study reveals the nonlinear influence of review topics, emotions, and environmental factors on visitation patterns in Las Vegas' parks and commercial environments, and how the pandemic altered the trajectory of visitor behavior recovery. Drawing on prior work that underscores threshold effects in urban processes, we confirm that linear models alone do not adequately capture the sudden shifts or the complex interdependencies that emerge when critical environmental thresholds are reached(Pickett et al., 2004). Unlike earlier big-data approaches focused mainly on physical parameters(He et al., 2018) or those relying on aggregate sentiment indicators (He et al., 2018; Zhang et al., 2018). Our BERT-based topic modeling framework integrates both objective measures (facility layouts, density, street width) and subjective dimensions (emotions, topics in reviews), offering a richer understanding of how and why visitors respond to changing urban conditions.

The recovery of health, fitness, entertainment, and social activities topic underscores the role of open spaces in meeting health and social needs. Social activities in parks recovered faster due to the demand for low-density, open environments, while activities in commercial spaces, like dining and entertainment, recovered more slowly due to concerns about confined spaces and distancing. This highlights the need for flexible space management in future public areas. Cities like Las Vegas should adopt decentralized, low-density spaces to enhance service flexibility, reduce crowding, and maintain quality social experiences, ensuring both social and health needs are met with adequate safety measures (Sallis et al., 2012).

Emotional fluctuations during the pandemic significantly impacted visitation (Cai et al., 2024), especially in commercial spaces where concerns about dense environments slowed emotional recovery. Managers should focus on optimizing safety and comfort to strengthen emotional connections and trust, creating welcoming environments for both shopping and leisure (Yatmo, 2009). In parks, positive emotions recovered quickly as the pandemic eased, demonstrating the importance of open natural spaces not only for recreation but for psychological restoration. Urban planning should prioritize expanding parks and green spaces to provide mental health benefits across various periods (Chen et al., 2024; Frumkin et al., 2017; Huai et al., 2022; Nesbitt et al., 2019).

In term of environmental factors, natural landscapes and facility layouts have a significant positive impact on visitation, promoting mental health (Kleinschroth and Kowarik, 2020). While these elements initially boost visitation, growth levels off after a certain threshold. Features like greenery, wide streets, and pedestrian-friendly sidewalks enhance comfort, security, and emotional satisfaction, but excessive expansion can diminish the visitor experience. For instance, overly wide streets may hinder social interaction, dense trees can feel confining, and large green spaces may encroach on pedestrian areas (Li et al., 2022), reducing opportunities for interaction and further improvement in visitor experience. These nuanced insights support the conclusion that *excessive expansion* can inadvertently *diminish* visitor experience, a pattern consistent with threshold-based nonlinear responses(Pickett et al., 2004; Zhang et al., 2018).

The pandemic heightened the public's need for psychological relief, leading many to turn to nature during lockdowns. Recent evidence indicates that the rapid rebound in urban park usage underscores a strong latent demand for outdoor spaces, suggesting that when critical social and emotional thresholds are surpassed, behavioral shifts occur swiftly (Ugolini et al., 2020). Future urban planning must balance natural landscapes with commercial development while ensuring accessibility and diversity. (Frumkin et al., 2017; Hartig et al., 2014), so that these spaces can provide emotional regulation and restoration during crises.

5.4. Strengths and limitations of the study

This study examines thematic differences between commercial spaces and parks, as well as the influence of environmental factors on visitation patterns. By combining social media reviews with street view data, we offer a fresh perspective on urban space functions and user experiences, capturing authentic emotions and preferences for urban planning. Additionally, the study considers external shocks, such as the pandemic, revealing the nonlinear influence of environmental factors and review topics on visitation behavior, which enhances our understanding of dynamic changes in urban space usage.

However, there are limitations. The data focuses on downtown Las Vegas, which may limit generalization to other regions with differing cultural, economic, and spatial contexts. While the model demonstrates high explanatory power, it may oversimplify the impact of factors like socioeconomic variables, industry dynamics, policy shifts, and individual characteristics. Second, our analysis relies solely on Google reviews for sentiment analysis, introducing potential demographic biases. Younger, more digitally engaged populations may be overrepresented, whereas older adults, technologically underserved communities, or groups preferring languages other than English might be underrepresented. This demographic skew could shape the sentiments and topics identified, meaning the results may not fully reflect the viewpoints of all user populations. Incorporating data from other social media platforms and additional sources could provide a more comprehensive perspective.

Third, a methodological limitation warrants consideration regarding our vegetation classification results. The apparent contradiction wherein "Plant" emerged as highly influential (importance score >0.5) while "Tree" demonstrated negligible influence in park settings stems from our semantic segmentation model's classification schema. The "Plant" category functionally subsumes various vegetation elements—including instances potentially classifiable as trees—resulting in artificial inflation of "Plant" scores and corresponding diminishment of "Tree" scores. This taxonomic aggregation reflects a technical constraint rather than suggesting trees' irrelevance to park greenery. Future research should employ refined vegetation classification frameworks that more precisely differentiate between plant typologies while acknowledging their collective ecological significance in urban environments.

Future research could expand by conducting comparative studies across various cities and cultural contexts to test the generalization of the findings. Additionally, integrating data from climate information could provide deeper insights into user behavior and preferences.

6. Conclusions

This study integrates multi-source data to explore the nonlinear relationships among environmental factors, review topics, and sentiment in urban visitation patterns, particularly in light of the pandemic's impact. Our approach provides new insights into the functions of urban spaces and their influence on urban vitality, revealing how these factors shape various environments. We recommend that urban planning and management consider both physical and emotional factors, with the flexibility to adapt to external shocks, to optimize urban spaces and improve user experiences. In commercial spaces, enhancing the physical environment and service efficiency remains key, while parks should prioritize emotional needs and experiences, especially during challenging times, to better promote visitation.

Future research should include more diverse data sources and broader urban contexts to improve generalization. Extending the study's timeframe would also allow for the analysis of long-term trends in environmental factors and user behavior, uncovering deeper mechanisms of influence.

In conclusion, this study emphasizes the importance of recognizing the nonlinear impacts of environmental factors and review topics on

visitation patterns. It underscores the need to address both physical and emotional elements across different environments and to adapt to nonlinear changes. This approach supports the development of more resilient strategies for urban planners and managers, enhancing the vitality and adaptability of urban spaces.

CRediT authorship contribution statement

Huang Yongming: Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Cai Yuxuan:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Li Xiaowei:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization, Project administration, Validation. **Yang Qiuyi:** Writing – original draft. **Wen Yuhan:** Writing – review & editing, Writing – original draft. **Chen Mingze:** Writing – review & editing, Writing – original draft, Data curation, Conceptualization. **Yang Zhuohao:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Data curation. **Chen Anzhi:** Writing – original draft, Methodology, Data curation, Conceptualization, Writing – review & editing.

Declaration of Competing Interest

No potential conflict of interest was reported by the authors.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ufug.2025.128835.

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