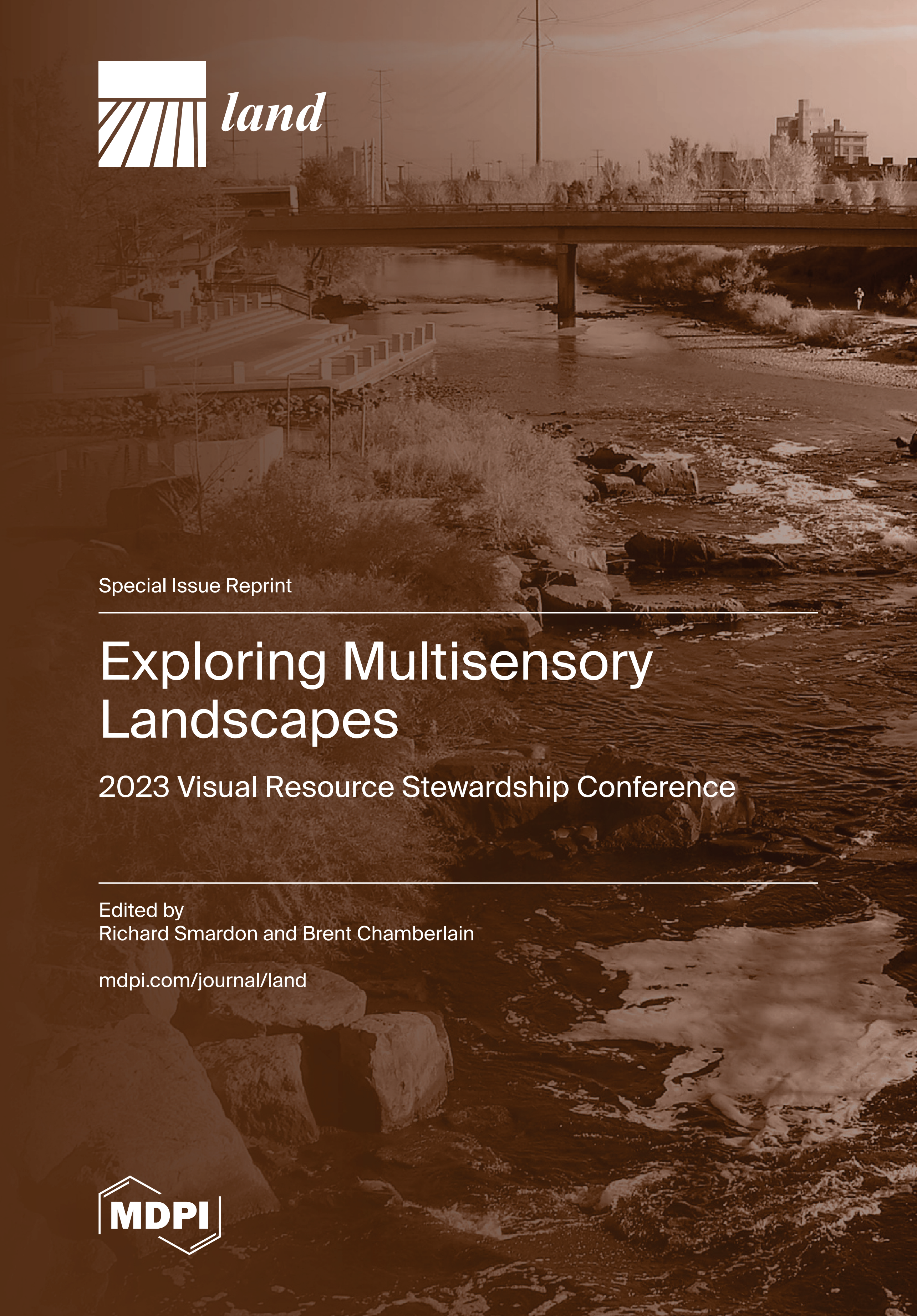

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Special Issue Reprint

Exploring Multisensory Landscapes

2023 Visual Resource Stewardship Conference

Edited by
Richard Smardon and Brent Chamberlain

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Exploring Multisensory Landscapes: 2023 Visual Resource Stewardship Conference

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Editors

Richard Smardon
Brent Chamberlain

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Contents

About the Editors

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Richard "Rick" Smardon is a SUNY Distinguished Service Professor Emeritus at SUNY/ESF. He has a Ph.D. in Environmental Planning from the University of California, Berkeley and a master's in landscape architecture and Bachelor's degree from the University of Massachusetts, Amherst. He has edited/written nine books the most recent being ***The Renewable Energy Landscape*** (2017), ***Revitalizing Urban Waterway Communities; Streams of Environmental Justice*** (2018) **Education for Sustainable Human and Environmental Systems** (2019) and ***Selected Papers from the 6th Fabos Conference on Landscape and Greenway Planning***. His new peer reviewed special journal issue entitled "Celebrating 25 Years of World Wetlands Day" builds on his 2009 book ***Sustaining the Worlds Wetlands: Setting Policy and Resolving Conflicts***. He co-produced the 2019, 2021 and 2013 Visual Resource Stewardship conferences and co-edited the 2017 Visual Resource Stewardship conference proceedings.

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Preface

This is the fourth international conference addressing visual resource stewardship. This special LAND issue purposefully sought to reach out to an international scholarly audience in addressing multisensory visual resource management issues particularly with the spirit of the EU Landscape Convention. We wish to acknowledge the contributions of the authors to this LAND journal special issue as well as the conference organizing committee members of the 2023 Visual Resource Stewardship Conference as well as the editorial staff of the LAND journal. A special acknowledge needs to be paid to Professor Robin Hoffman PhD who has been critical to the visual resource stewardship conferences of 2019, 2021 and 2023.

Richard Smardon and Brent Chamberlain
Editors

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Editorial

Overview for Exploring the Multisensory Landscape

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Land use change has had a fundamental impact on the livelihoods of people throughout the world. This Special Issue focuses on the research being conducted at the intersection of this land use change and the importance of maintaining landscapes that enrich humanity and our engagement with nature. Within this Special Issue, we explored the value of landscapes that heighten the senses. Visual Resource Stewardship is an area of research that closely aligns with understanding how changes in the environment may be perceived and experienced. Understanding the tools, processes, and theories involved helps us to better understand how land use change impacts humanity, which is a critical endeavor in landscape planning.

The goal of this Special Issue is to catalyze ideas and innovations between academia, practice, NGOs, and government agencies working to address the analysis, planning, valuation, design, and management of visual resources. We sought papers that investigate, exemplify, or theorize on the protection of visual resources in an era of major landscape changes on a regional, national, and global scale. This Special Issue also invites submissions that deal with multi-sensory topics at the intersection of people and the environment.

This Special Issue welcomed manuscripts that address the following themes:

- Multisensory landscape assessment;
- Visual quality and context sensitive design;
- Scenic resource valuation;
- Representation methods and systems used in assessments of visual perceptions;
- The visual effects of climate change and renewable energy.

This Special Issue stems from the fourth Visual Resource Stewardship Conference, which is part of the biennial conference series held in 2017, 2019, 2021, and 2023. The aim of these conferences is to share ideas and discuss issues associated with the assessment and protection of visual resources in an era of continued and new landscape changes—regionally, nationally, and globally. The articles from the 2017 conference have been published by Gobster and Smardon [1], and selected papers from the 2019 and 2021 conferences have been published in a Land Special Issue journal edited by Chamberlain, Hoffman, and Smardon [2].

The twelve papers within this Special Issue cover the range of themes mentioned above within the List of Contributions. Three articles address the means of assessing landscapes for different purposes. Miller et al. have developed a user-friendly means of identifying scenic viewsheds in Virginia, USA. Shen et al. have developed a method for assessing rural landscapes for restoration potential in China. Faidon et al. have developed a cumulative index for management and protection for cultural and natural heritage areas in the Parrhasion Heritage Park in Peloponnese, Greece.

Three articles specifically address multisensory landscape studies. Finnigan assessed perceived relationships between outdoor built environments and sensory sensitivities, focusing on autism, ADHD, and dyslexia. Li et al. used virtual reality and machine learning to assess residents' perceptions of residential landscape space in both non-snow and snow seasons. Li et al. assessed the emotional impact of high-density urban river spaces in Liangma River, China, using both qualitative questionnaires and quantitative physical data.

Two articles by Miller and Evans and Chamberlain critique the use of eye tracking methods for landscape visual assessment. Yao and Sun use preference questionnaires and eye movement heat maps to identify rural landscape visual quality in Southwestern Guihou, China. Jaing et al. analyze the tourist-perceived physical and aesthetic quality of rural settlements in Zhaoxing Dong village in China. Dunkel and Burghardt review the utilization of user-contributed data to assess perceived landscape change both spatially and temporally. Last, Gao et al. offer a systematic literature review of methods for assessing highway right-of-way visual quality.

All of the aforementioned manuscripts illustrate the use of new quantitative and qualitative methods in assessing people's perception of the multisensory environment given the challenges of landscape change, both spatially and temporally.

The editors wish to thank all the authors of the contributed papers to this Special Issue as well as the Land Journal editors, whose assistance is critical to processing these articles. We wish to acknowledge Professor Emeritus Robin Hoffman of the SUNY College of Environmental Science and Forestry, who was critical to the production of the 2023 Visual Resource Management Conference, Exploring the Multisensory Landscape.

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List of Contributions

1. Miller, P.; Sim, J.; Powell, L.; Crump, L. Scenic Assessment Methodology for Preserving Scenic Viewsheds of Virginia, USA. *Land* **2024**, *13*, 1010. https://doi.org/10.3390/land13071010.
2. Shen, H.; He, X.; He, J.; Li, D.; Laing, M.; Xie, X. Back to the Village: Assessing the Effects of Naturalness, Landscape Types, and Landscape Elements on the Restorative Potential of Rural Landscapes. *Land* **2024**, *13*, 910. https://doi.org/10.3390/land13070910.
3. Faidon, G.; Papakonstantinou, D.; Papadopoulou, N.P. Geohazard Prevention Framework: Introducing a Cumulative Index in the Context of Management and Protection of Cultural and Natural Heritage Areas. *Land* **2024**, *13*, 1239. https://doi.org/10.3390/land13081239.
4. Finnigan, K. A. Sensory Responsive Environments: A Qualitative Study on Perceived Relationships between Outdoor Built Environments and Sensory Sensitivities. *Land* **2024**, *13*, 636. https://doi.org/10.3390/land13050636.
5. Li, X.; Huang, K.; Zhang, R.; Chen, Y.; Dong, Y. Visual Perception Optimization of Residential Landscape Spaces in Cold Regions Using Virtual Reality and Machine Learning. *Land* **2024**, *13*, 367. https://doi.org/10.3390/land13030367.
6. Li, M.; Lui, K.; Zhang, S.; Wu, D. The Effect of Perceived Real-Scene Environment of a River in a High-Density Urban Area on Emotions. *Land* **2024**, *13*, 35. https://doi.org/10.3390/land13010035.
7. Miller, P.A. Eye-Tracking and Visual Preference: Maybe Beauty Is in the Eye of the Beholder? *Land* **2024**, *13*, 598. https://doi.org/10.3390/land13050598.
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12. Gao, H.; Bakar, S.A.; Maulan, S.; Yusof, M.J.M.; Munder, R.; Chen, B. How Highway Landscape Visual Qualities Are Being Studied: A Systematic Literature Review. *Land* **2024**, *13*, 431. https://doi.org/10.3390/land13040431.

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Article

Scenic Assessment Methodology for Preserving Scenic Viewsheds of Virginia, USA

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Abstract: The non-profit organization Scenic Virginia is dedicated to identifying and showcasing the state's scenic landscapes. Recently, the state incorporated a "scenic" element into its new Conserve Virginia land conservation strategy. Consequently, there is a need for a standardized assessment tool that both citizens and professionals can use to identify and evaluate the scenic value of publicly accessible viewsheds in Virginia. This paper outlines the rationale behind developing a scientifically robust protocol, which is based on an extensive literature review and photographs from Scenic Virginia's annual photo contest. The protocol serves as a scenic assessment tool designed to encourage local citizen participation in identifying significant scenic resources in Virginia. Local communities will utilize this new tool to help them identify and evaluate their scenic assets. The protocol was reviewed by a panel of experts, and its implementation is currently underway.

Keywords: scenic; viewshed; visual; assessment; landscape; VRM; communities

1. Introduction

Evaluating scenic landscapes has been a crucial aspect of environmental planning, urban development, and conservation efforts for a long time. Throughout the years, numerous tools and methods have been developed to assess and manage landscapes efficiently, demonstrating a wide array of approaches influenced by both scientific research and aesthetic considerations. As landscape architecture continues to advance, the methodologies used to assess and protect these essential resources have also become more sophisticated.

Historically, research on landscape evaluation has assessed natural elements within the landscape by evaluating their physical characteristics through the formal aesthetic model [1], ecological value and rarity through the ecological model [2], observers' responses to elements within the landscape through the psychological model, and observers' overall preferences for the landscape through the psychophysical model [3]. These landscape evaluation models can be classified based on how experts or observers evaluate the components of the landscape or the landscape as a whole. One indicator not considered in traditional landscape evaluation models is the aspect of landscape use. External factors such as the users of the landscape are excluded from the aesthetic, psychological, and ecological evaluations of the landscape itself. Recently, as the use of landscape resources has increased, factors such as who uses the landscape and to what extent can also be considered as indicators in the evaluation of landscape resources.

Recent advancements in landscape assessment research reflect a shift towards more integrated and technologically driven approaches, recognizing the increasing complexity of landscapes and the multifaceted impacts of human activity on ecological and aesthetic values. The use of geographic information systems (GIS) and remote sensing technology has become prevalent, allowing for more precise and comprehensive data collection and analysis [4]. Increasingly, researchers are utilizing data from social media platforms as a

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form of public input into landscape assessments. By analyzing geotagged photos and posts, researchers can gather large volumes of data on public usage and preferences concerning different landscapes [5]. Reflecting ongoing interest in the individual's experience of the landscape, phenomenological research continues to evolve. This approach is concerned with understanding the subjective and emotional responses individuals have towards landscapes [6].

Much of the research on landscape assessment is fundamentally based on traditional frameworks that have been historically studied. However, significant value can be added through the application of new analytical methods. An increasing reliance on data analysis means that using these assessment techniques can be challenging for individuals without specialized software skills. As such, there is a pressing need for research that develops user-friendly methods for evaluating and conserving valuable landscapes in practical settings.

Furthermore, complex assessment methods can present challenges in accurately capturing the opinions of local residents. This research emerged from a practical perspective, acknowledging Virginia's renowned natural beauty within the United States. When people hear that someone lives in Virginia, they often remark, "Oh, Virginia is so beautiful". The state boasts a diverse array of landscapes from the Chesapeake Bay shorelines to the Blue Ridge Mountains, enriched by a deep history of human habitation. These cherished landscapes are a heritage treasured by Virginians, yet they face threats from urban sprawl and uncontrolled development. What can be done to protect them? A scenic viewshed register might highlight the views valued by the Commonwealth's citizens. What would be required to achieve this? Both the state and its residents are dedicated to preserving these landscapes through various initiatives. Scenic Virginia, for instance, aims to identify and manage crucial scenic resources by creating landscape assessment models. This study lays the groundwork for developing models to discover and evaluate scenic resources in Virginia, facilitating more effective management and conservation decision making.

This paper is organized into four main sections: background, literature review, scenic viewshed assessment methodology, and results and discussion. The Background Section outlines the necessity of a viewshed assessment procedure, the role of Scenic Virginia, the significance of public involvement, the definition of a viewshed, details of the scenic viewshed research project, and the process by which Scenic Virginia will identify scenic viewsheds. The Literature Review Section highlights variables identified through literature review that were incorporated into the assessment methodology, using photographs from the Scenic Virginia View photograph contest for comparison. The Methodology Section explains and implements the final viewshed assessment methodology. The results of the project are presented, followed by a discussion of concluding observations.

2. Literature Review

2.1. Landscape Assessment

2.1.1. Landscape Assessment Theories

Many landscape assessment tools have been developed and used for a long period of time. Landscape assessment models have been classified in various ways by different researchers. Among them, classical models were reviewed. Arthur, Daniel, and Boster (1977) split them into descriptive inventories and public preference models [7]. Zube, Sell, and Taylor (1982) divided the models into four landscape perception paradigms: the expert, psychophysical, cognitive, and experimental [8]. Briggs and France (1980) used direct and indirect methods to divide scenery assessment into classificatory and non-classificatory methods [9]. Among these methods, this literature review section follows Daniel and Vining's classification. Daniel and Vining (1983) split the landscape assessment into four categories: formal aesthetic, psychophysical, psychological, and ecological models. Their classification logic is well suited to landscape architects who expect phenomenological models since the phenomenological models are focused on the individual's perception of their experiences rather than evaluation of the landscape [10].

Peng and Han (2018) categorized and summarized models for evaluating landscapes based on era, purpose (theoretical type and practical type), and methods. According to their research, landscape evaluation models have developed over three stages: The first stage, from 1967 to 1971, includes the phenomenological model, formal aesthetic model, and ecological model. The second stage, from 1971 to 1976, includes the psychology model and psychophysical model. The third stage, from 1973 to the present, includes the land use assumption and fuzzy logical system model [11]. In this study, landscape evaluation models are categorized based on the distinctions of purpose and method identified in Peng and Han's research, as shown in Table 1.

Table 1. Classification of Seminal Landscape Assessment Models.

Category	Evaluation	Preference
Theoretical	Ecological model -Unique ratio [2]	Psychological model -Information-processing theory [3]
Empirical	Formal aesthetic model -Forest landscape description and inventories [1] -Visual management system [10,12] -Scenery management system [13] -Combined landscape value [14]	Psychophysical model -Natural landscape preference prediction [15] -Scenic beauty estimation [16] -Predicting scenic beauty [17]

The formal aesthetic model is focused on inherent aesthetic values in the formal properties of the landscape. Landscape features such as essential forms, lines, colors, and textures can be evaluated for their contribution to intrinsic aesthetic quality. Landscape architects analyze interrelationships between essential elements such as the harmony, unity, contrast, and variety in assessing aesthetic value [10]. For this model, trained experts firstly analyze the formal visual characteristics of the landscape such as lines, forms, textures, and color. Then, they assess the interrelationships among the basic elements in terms of variety, unity, and integrity. This model requires understanding landscape elements and their relationship and can be applied to general landscapes. Application requires some knowledge or training.

The classical psychophysical model is the combination of two fields: the physical and the psychological. The theoretical background of this model is the relationships between physical features in the landscape and human perceptual responses [10]. The model seeks to identify mathematical relationships between the physical elements of the landscape and the psychological responses of human observers [15,18]. The physical elements are measured by experts and preferences are evaluated by empirical surveys. Psychophysical models have been used in many practical settings. For securing the validity of this model, many landscape scenes and multiple observers are employed. The purpose of this paper is to describe the development of a model that predicts a people's perceptions of landscape quality based on physical features of the landscape [10].

Unlike the formal aesthetic model, which emphasizes the viewer's understanding of the characteristics of the landscape, the psychophysical model prioritizes the viewer's perception and preference. In this model, the viewer's preference determines the value of the landscape. Thus, the overall preference for the landscape is more important than its specific features or major elements. A representative study within the psychophysical model is the information-processing theory, which is considered the most significant in landscape preference research [19]. According to this model, an individual's judgment of a landscape depends on two fundamental responses: understanding and exploration [3]. Kaplan and Kaplan (1989) identified four key informational characteristics based on these responses: coherence, complexity, legibility, and mystery. Coherence refers to the order within the landscape, while complexity denotes the variety of visual elements within a landscape. Legibility indicates how easily the landscape can be understood and remembered. Lastly, mystery is the quality that motivates an individual to take a step further into the landscape [3].

Ecological models originated from general concern for the protection of the natural environment. The environmental movement of the 1960s reinforced concern for pollution of the environment and warned about the harm of careless developments. Leopold was interested in inventorying river valleys to find an appropriate site for dam construction. Basically, Leopold believed that unique landscapes hold more significance than common landscapes. His rationale is that "landscape which is unique. . .has more significance to society" [2]. Also, the unique qualities enhance its value to society. He raised three questions to develop the model: (1) What criteria can be used to judge a given piece of the landscape? (2) What other landscapes or features can it be compared with? (3) How can any set of landscapes be ranked by priority [2]? Based on those questions, he proposed a methodology to present a unique ratio.

A review of key prior studies on landscape assessment theories reveals that evaluating landscapes involves both their physical characteristics and the emotional responses of users who view them. While the physical attributes of the landscape represent objective features, the perspective of the observers is more subjective. Therefore, it is essential to consider both objective and subjective perspectives in landscape evaluation.

2.1.2. Recent Trends in Landscape Assessment Tools

Recent advancements in landscape assessment theory have significantly integrated technologies, particularly geographic information systems (GIS), to enhance environmental management and decision-making processes [20–22]. These technologies provide robust solutions for utilizing diverse land data sources, aiding in the analysis of landscapes and developing sustainable planning strategies [23]. Methods such as viewshed and landform studies are employed to model landscape factors and create maps for spatial analyses, investment decisions, and monitoring landscape changes over time [24]. Furthermore, the application of landscape connectivity in suitability evaluations, especially in urban ecologically sensitive areas, has optimized ecosystem planning [25]. This is achieved by incorporating hydrological analysis tools in GIS, offering a more comprehensive assessment approach. These advancements underscore the evolving landscape assessment theories that leverage technological innovations for more effective and sustainable landscape management practices.

Ivantsova and AI-Chaabawi (2022) assessed agroforestry landscapes using GIS and remote sensing technologies to identify and mitigate negative factors leading to soil depletion. The use of innovative resource-saving technologies was emphasized to prevent degradation and restore soil fertility [20]. Roth, Nalim, and Krech (2018) provided a qualitative assessment of screening technologies for medicine quality assurance across ten countries, highlighting significant gaps in technology development, evaluation, and information dissemination. The study revealed wide variations in the understanding and usage of these technologies and identified the ideal qualities for the next generation of screening technologies [21]. It emphasized the need for objective technical reviews and better financial resource information. Chételat (2005) discussed the integration of landscape assessment theory with geographic information systems (GIS) for effective landscape evaluation and management strategies. The study proposed a participative multiscale landscape assessment method using GIS, emphasizing the importance of combining qualitative landscape evaluations with quantitative GIS systems to enhance environmental management and negotiation processes [22]. Ozimek and Ozimek (2017) examined the underutilization of digital technologies in landscape assessment and planning. By employing viewshed and landform studies, the research demonstrated the effectiveness of these methods in modeling landscape factors [23]. The findings suggested that these technologies can significantly enhance spatial analyses, decision making, and land management processes. Shaoyao (2013) applied landscape connectivity theory to urban ecology suitability assessment, utilizing hydrological analysis tools in ArcGIS to optimize suitability analysis. The study highlighted how this approach can improve the evaluation and optimization of land suitability, contributing to better urban ecological planning and management [24].

Through these studies, the development and utilization of GIS, remote sensing, and digital analysis tools for landscape evaluation methods have been reviewed. Previous research focused on studying the concepts of landscape evaluation and employed various methods to understand these concepts. In contrast, recent research has emphasized replacing traditional methods with various technologies based on concepts derived from earlier studies. Consequently, there is a growing gap between the approaches of lay people or experts unfamiliar with the latest technologies and that of recent research.

2.2. Viewshed Recognition Program

2.2.1. U.S. National Program

This section reviews two national-level landscape assessment and preservation tools in the United States: The National Scenic Byways Program and National Heritage Areas (NHA). Both programs aim to protect and promote the nation's significant scenic, cultural, and historical landscapes, albeit through different approaches and management structures (Table 2).

Table 2. National Viewshed Recognition Program.

Feature	National Scenic Byways Program	National Heritage Areas
Developed Year	1991	1984
Administered by	Federal Highway Administration (FHWA)	National Park Service (NPS)
Purpose	Recognize and promote roads with outstanding qualities	Preserve and promote cohesive, nationally important landscapes
Designation Criteria	Scenic, historic, cultural, natural, recreational, archaeological	National heritage significance, local support, feasibility
Management	Federal, state, and local partnership	Local coordinating entities with NPS assistance
Funding	Grants and funding from FHWA	Federal funds with matching local/state funds
Benefits	Tourism enhancement, economic development, resource preservation	Resource preservation, heritage tourism, community involvement

The National Scenic Byways Program, established in 1991 and administered by the Federal Highway Administration (FHWA), recognizes roads throughout the United States for their outstanding scenic, historic, cultural, natural, recreational, and archaeological qualities. This program aims to preserve and enhance these corridors, transforming them into travel destinations that offer unique and enriching experiences. Roads are nominated based on their exceptional qualities and require a comprehensive corridor management plan to maintain these attributes. The program promotes local and state involvement in the designation and preservation processes and provides grants and funding to support these efforts [26]. This tool emphasizes the program's role in boosting tourism and local economic development. By enhancing the travel experience, scenic byways attract visitors, which can lead to increased spending in local communities. Additionally, the program raises awareness about the importance of preserving scenic and cultural resources, contributing to broader conservation efforts [26].

In contrast, the National Heritage Areas (NHA) program, initiated in 1984 and managed by the National Park Service (NPS), focuses on areas where natural, cultural, and historic resources create a cohesive, nationally significant landscape. The NHA designation involves a thorough feasibility study and demonstrates widespread local support. Once designated, these areas are managed through local coordinating entities such as nonprofit organizations or local governments, with technical assistance from the NPS [27]. NHA emphasizes community involvement and partnership. The management strategy for these areas is collaborative, involving local communities, state and federal governments, and private organizations. This approach encourages sustainable economic development through heritage tourism and fosters a sense of pride and stewardship among residents. Funding for NHA includes federal support, which must be matched by local or state contributions, promoting additional public and private investment [28].

While both programs share a common goal of preserving and promoting significant landscapes, their methodologies and focus areas differ. The National Scenic Byways Program is road-centric, emphasizing the preservation and enhancement of specific corridors with outstanding qualities. It relies heavily on state and local participation and provides federal grants to support these efforts. In contrast, NHA focuses on broader landscapes with cohesive natural, cultural, and historical significance, leveraging local partnerships for comprehensive management and preservation.

The literature highlights that both programs contribute significantly to conservation and sustainable tourism. However, their success relies on strong community involvement and effective collaboration among various stakeholders. By comparing these two programs, this review underscores the importance of tailored approaches to landscape preservation that address specific regional and community needs while promoting national heritage and tourism [29].

2.2.2. The U.S. State Program

This section examines various state-level landscape assessment and preservation tools in the United States, focusing on the California Scenic Highway Program, Colorado Scenic and Historic Byways, Oregon Scenic Byways, Virginia Scenic Roads and Byways, Florida Scenic Highways Program, and Texas Scenic Byways and Historic Highways. Each program is designed to protect and enhance the scenic, historical, and cultural values of specific routes or areas, thereby promoting sustainable tourism and local economic development (Table 3).

Table 3. State Viewshed Recognition Programs.

Program	Developed Year	Focus Areas	Administered by	Community Involvement
California Scenic Highway Program	1963	Scenic preservation, corridor protection	California Department of Transportation	High
Colorado Scenic and Historic Byways	1989	Scenic, historical, cultural, recreational values	Colorado Department of Transportation	High
Oregon Scenic Byways	1989	Scenic, historic, cultural significance	Oregon Department of Transportation, Travel Oregon	High
Virginia Scenic Roads and Byways	1966	Scenic, historical, cultural values	Virginia Department of Transportation	Medium
Florida Scenic Highways Program	1996	Natural, cultural, historical resources	Florida Department of Transportation	High
Texas Scenic Byways and Historic Highways	1995	Scenic, historical importance	Texas Department of Transportation	High

The California Scenic Highway Program, developed in 1963, aims to preserve and enhance the natural beauty along the state's highways. It encourages local governments to adopt ordinances that protect scenic quality, focusing on a corridor approach that assesses viewsheds from the highway. This program involves rigorous scenic corridor protection plans to maintain the visual appeal of these routes [30]. Similarly, the Colorado Scenic and Historic Byways program, established in 1989, promotes routes with exceptional scenic, historical, cultural, and recreational values through a community-based nomination process. This program integrates tourism, preservation, and education and is managed by the Colorado Department of Transportation in partnership with local communities [31].

In Oregon, the Scenic Byways program, also initiated in 1989, highlights roads with significant scenic, historic, and cultural importance. The program emphasizes enhancing travel experiences while supporting local economies through comprehensive route planning and marketing efforts. It is a collaborative effort between the Oregon Department of Transportation and Travel Oregon [32]. The Virginia Scenic Roads and Byways program, established in 1966, identifies routes with significant scenic, historical, and cultural values. Scenic designations require an application process and approval by the Commonwealth Transportation Board. This program supports preservation efforts and promotes tourism, with the Virginia Department of Transportation working closely with localities for designation and promotion [33].

The Florida Scenic Highways Program, developed in 1996, focuses on showcasing the state's natural, cultural, and historical resources. It operates as a community-based program where local groups nominate roads for designation. The program provides grants and technical assistance for corridor management planning and is managed by the Florida Department of Transportation with significant local community involvement [34]. The Texas Scenic Byways and Historic Highways program, initiated in 1995, promotes routes with significant scenic and historical importance. It involves a state-designated process with criteria for scenic, historical, cultural, recreational, and natural qualities, encouraging preservation and enhancement of scenic resources. The program is managed by the Texas Department of Transportation with input from local communities and stakeholders [35].

Each of these programs shares the common goal of preserving scenic, historic, and cultural values while promoting sustainable tourism and local economic development. They differ mainly in their management structures and the specifics of their assessment and community involvement processes. The California, Colorado, Oregon, and Florida programs demonstrate high community involvement, integrating local groups into the nomination and management processes. In contrast, Virginia's program medium incorporates local community involvement with a more structured application and approval process. The Virginia program builds on what people like and prefer in their own communities. Despite these differences, all programs contribute significantly to conservation and sustainable tourism, underscoring the importance of tailored approaches to landscape preservation that address specific regional and community needs.

2.2.3. Implications from Viewshed Recognition Program

A successful viewshed recognition program requires two key components. First, there must be an understanding of visual assessment principles and previous research in the field. To this end, Scenic Virginia enlisted researchers from Virginia Tech University to conduct a literature review and identify the key concepts and variables that have been used to define what is "scenic". Second, a method for evaluating the viewsheds of local residents and communities is essential. Historically, most visual assessments have been conducted on public lands by agencies like the U.S. Forest Service and the Bureau of Land Management. However, viewshed management in Virginia will encompass both private and public lands, with an emphasis on preserving scenic quality.

Scenic Virginia, a non-profit organization, values the scenic beauty of Virginia's landscapes. Scenic Virginia plays a crucial role in the evaluation and preservation of the state's scenic landscapes, working to identify, celebrate, and protect Virginia's most beautiful and culturally significant vistas. For instance, Scenic Virginia has been instrumental in promoting scenic byways as tools for scenic resource protection. Their involvement in initiatives like the Virginia Scenic Byways program, which is managed in partnership with the Virginia Department of Transportation (VDOT) and the Department of Conservation and Recreation (DCR), underscores their commitment to preserving critical scenic resources. The Virginia Scenic Byways program, introduced in 1999, designates roads with exceptional scenic, historical, cultural, and recreational values, aiming to enhance travel experiences and support local economies by attracting tourists and fostering community pride.

Scenic Virginia plays a potentially crucial role in the proposed viewshed register program by representing the voices of Virginians who understand that the state's scenic landscapes are vital to their quality of life, essential for a robust economy, and key to attracting jobs. Additionally, preserving these landscapes is a legacy for future generations. This paper outlines a protocol or scenic assessment tool developed from pertinent concepts and theories found in the literature, along with an assessment process that actively involves the local public in a viewshed register initiative.

(1) Public engagement

In the United States, several landscape photographic contests effectively engage public participation in landscape preservation and appreciation. The USA Landscape Photographer of the Year contest showcases the nation's diverse landscapes, from national parks to urban scenes, and includes a public voting component to encourage broader engagement. Similarly, the National Geographic Photo Contest invites photographers to capture stunning landscapes, featuring winning images in widely accessible publications and online platforms, thereby fostering public interest in environmental conservation. The Audubon Photography Awards, while primarily focused on bird photography, highlight significant natural landscapes and engage the public through exhibitions and online galleries, promoting habitat preservation.

A viewshed registry program needs to gain official recognition from the State of Virginia to be formally established. Consequently, involving the public in the identification of scenic viewsheds is critical for the program's success. Scenic Virginia stands out as the perfect organization to facilitate this public involvement. Additionally, landscape architects from the Virginia Department of Recreation and Conservation—responsible for the Virginia Scenic Rivers and Virginia Byways programs—will play a crucial role in aligning the program with state requirements.

Scenic Virginia will manage the viewshed registry process, leveraging its broad public support, built over years through initiatives like its annual scenic landscape photo contest. The organization has a proven track record of collaborating with both the public and local government officials to recognize and preserve scenic landscapes. It is expected that most viewshed nominations will come from non-experts, so the nomination form must include detailed descriptions to help Scenic Virginia decide if a nomination should advance to the scenic quality evaluation stage. Nominations will be accepted from a diverse range of sources, including citizens, landowners, government officials, and local grassroots groups.

The landscape assessment tool developed in this study uniquely integrated the perspectives of the general public by utilizing photographs taken by non-professional photographers. This approach ensures that the tool reflects the community perceptions and values unique to the scenic landscapes of Virginia rather than solely relying on the assessments of professional landscape architects, which might not capture the broader public's views. By developing an assessment tool that was evaluated by using photographs from general public through photographic contests, the study acknowledges and incorporates the everyday experiences and aesthetic appreciations of ordinary people. This method also mitigates potential conflicts of interest and pressures related to community economic development and regional planning shortcomings, providing a more democratic and comprehensive understanding of scenic resources. Thus, this approach not only enriches the landscape assessment by diversifying the input but also justifies the decision to forego exclusive reliance on professional experts, ensuring the results are more aligned with public sentiment and local cultural values.

(2) View and Viewshed

Visual perception significantly influences how individuals interpret and evaluate landscapes, particularly regarding "view" and "viewing" aspects. This foundational understanding is essential for appreciating both the aesthetic and functional values of landscapes. Appleton's (1975) "prospect-refuge" theory highlights that humans prefer landscapes offering both views (prospect) and shelter (refuge), reflecting deep-rooted evolutionary preferences [36]. Similarly, Kaplan and Kaplan (1989) developed the "preference matrix", identifying coherence, complexity, legibility, and mystery as crucial factors shaping landscape preferences [3]. These theories underscore that visual perception in landscape interpretation is multifaceted, deeply rooted in psychological and evolutionary principles, and critical for contemporary landscape evaluation.

Recent studies have expanded on these foundational theories to address modern landscape assessment needs. Gobster and Chenoweth (1989) conducted a quantitative analysis, identifying naturalness, visual diversity, and maintenance as significant factors in landscape perception [37]. Nassauer (1995) emphasized the role of cultural norms and visual cues, arguing that orderly and well-managed landscapes are generally preferred [38]. Daniel and Vining (1983) explored various methodological approaches to landscape quality assessment, underscoring the importance of visual perception [10]. Sevenant and Antrop (2010) demonstrated the application of perception studies in landscape planning, showing how public perception can inform landscape identity development and enhance planning processes [39]. By integrating these insights into our study, we provide a more comprehensive discussion on how visual perception and public engagement in landscape image evaluation contribute to a nuanced understanding of landscape aesthetics and functionality.

The concept of "viewshed" is inspired by the idea of a watershed. A watershed is an area where all the rainfall converges and flows past a specific point. Similarly, a viewshed encompasses the entire 360-degree area visible from a particular point, known as a viewpoint. However, parts of this area are often obscured by elements like vegetation, terrain, or other obstacles (refer to Figure 1). A "defined viewshed" specifically refers to the visible segment from a certain viewpoint, characterized by its viewing direction, width, and distance. In this article, the term "viewsheds" is used to denote these "defined viewsheds".

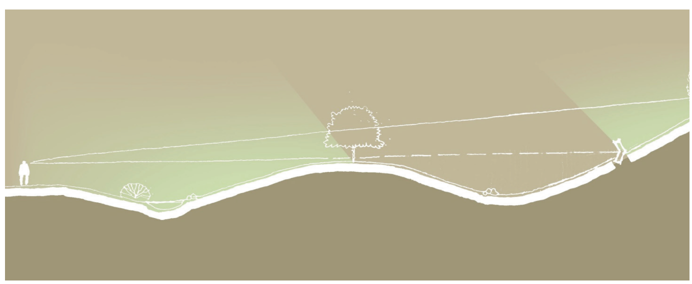


Figure 1. The area visible from the viewpoint may be blocked by vegetation, topography or other objects. A viewpoint is defined by its view direction, view width, and view distance.

(3) Scenic Quality

Scenic quality, a crucial measure of the scenic importance of a viewshed, is based on human perceptions of the intrinsic beauty of landforms, water characteristics, and vegetation patterns. When combined, these attributes determine a landscape's intrinsic scenic beauty. Scenic quality, often described as the product of the landscape according to the reactions of a person experiencing that landscape [40–42], is a critical factor in landscape assessment. It depends upon perception and reflects the particular combination and pattern of elements in the viewshed [43]. When viewed by people, these are the essential attributes of landscape that evoke positive physiological and psychological reactions, thereby influencing society in general.

Regarding the qualitative aspects of the landscape, previous literature reviews have examined theories and concepts related to landscape elements, the components that constitute landscapes, and tools for evaluating landscape quality. Through this literature review, the necessary concepts and elements required for developing the landscape assessment tool in this study were identified and extracted. The following terms and concepts from the related literature were determined to be helpful in assessing scenic viewsheds:

- Physiographic province or region [44–47];
- Distance zones and scale [1,12,13,48];
- Diversity, variety, and visual complexity [7];

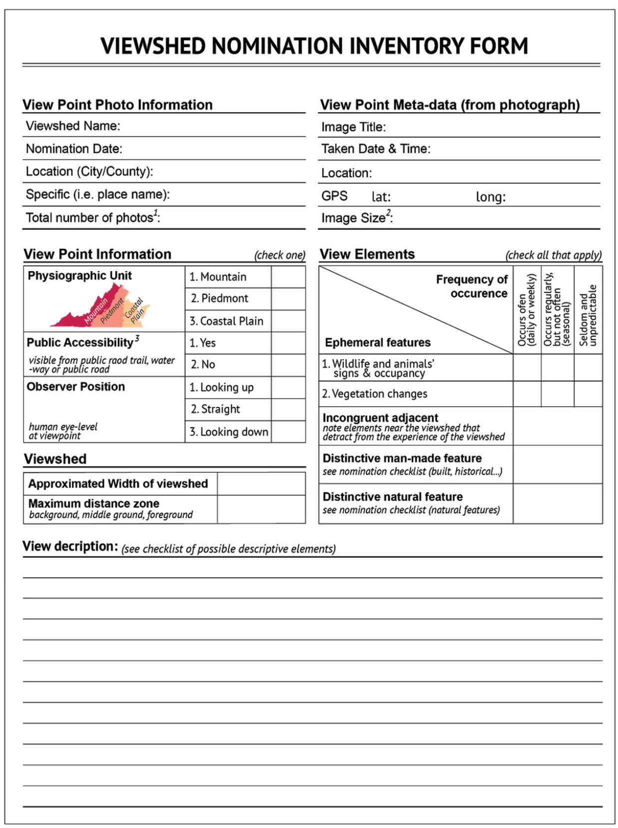
- Coherence and legibility [49];
- View type [50];
- Viewer position [50,51];
- Visual sensitivity or public awareness [52].

3. Scenic Viewshed Nomination and Scenic Assessment Process

3.1. Nomination Inventory

Nominators are not required to have knowledge of scenic assessment procedures. They might be government officials, landscape architects, or local citizens. They will use a nomination form and a checklist of potential landscape features. Figure 2 depicts the nomination form. The first part of the viewshed designation process is the viewshed nomination. The nomination should include the following basic descriptive information:

- Viewshed name (place name);
- Date of nomination;
- Location (city or county);
- Viewpoint location (GPS point and compass direction for the view angle);
- Physiographic unit;
- Viewshed physical area (approximate width and view distance).



VIEWSHED NOMINATION INVENTORY FORM

View Point Photo Information
- Viewshed Name:
- Nomination Date:
- Location (City/County):
- Specific (i.e. place name):
- Total number of photos[1]:

View Point Meta-data (from photograph)
- Image Title:
- Taken Date & Time:
- Location:
- GPS lat: long:
- Image Size[2]:

View Point Information (check one)

Physiographic Unit (Mountain, Piedmont, Coastal Plain)	1. Mountain	
	2. Piedmont	
	3. Coastal Plain	
Public Accessibility[3] *visible from public road trail, water -way or public road*	1. Yes	
	2. No	
Observer Position *human eye-level at viewpoint*	1. Looking up	
	2. Straight	
	3. Looking down	

Viewshed

Approximated Width of viewshed	
Maximum distance zone *background, middle ground, foreground*	

View Elements (check all that apply)

Ephemeral features / Frequency of occurence	Occurs ofen (daily or weekly)	Occurs regularly, but not often (seasonal)	Seldom and unpredictable
1. Wildlife and animals' signs & occupancy			
2. Vegetation changes			
Incongruent adjacent *note elements near the viewshed that detract from the experience of the viewshed*			
Distinctive man-made feature *see nomination checklist (built, historical...)*			
Distinctive natural feature *see nomination checklist (natural features)*			

View decription: *(see checklist of possible descriptive elements)*

1. up to three photos, one must be from viewshed view point
2. a minimum size of 1024 megapixels
3. must be accessible to be nominated (e.g. trails, roads, public recreation zones and other)

Figure 2. Scenic Viewshed Nomination Form. It is anticipated that this form may change as insights are gained from implementation of the procedure.

The viewshed must be accessible by the public (accessible from a public accessway). The nomination should include a maximum of three photographs, with one required photo from the viewshed viewpoint. Meta-data from the photographs should be included (1024 pixels is the minimum photograph resolution [53]) .

A written description of the viewshed should be included in the nomination. The description should identify distinctive natural features (including predictable and relatively frequent ephemeral qualities or qualities that change regularly over time, such as seasonal color and migratory birds), and positive manmade features should be identified and described (features that seem to be in harmony with the landscape or past use of the landscape). Incongruent or negative features (features that do not seem to fit in the landscape or feel out of place) visible from the viewshed should also be listed. Public awareness of and interest in the viewshed should be included in the nomination description as well as any potential threats to the scenic quality of the viewshed. This might include newspaper articles, public meetings, and concerns expressed over possible land development within the viewshed. Nominators will use a nomination form and a checklist of potential landscape features. Figure 2 depicts the nomination form.

3.2. Sample Photographs from the Scenic Virginia Landscape Photo Contest

Photographs from the Scenic Virginia photo contests were examined to determine if the variables identified earlier in the literature were adequate to assess the scenic quality of Virginia landscapes. The photographs from the Scenic Virginia photo contest were submitted by citizens of Virginia who believed that the photo captured a landscape that was scenic. Many photos were selected from past contests to represent the range of landscape types in Virginia. The final set of photographs used in this study was carefully selected to represent the landscapes of Virginia. Photographs that included mainly the photographer's artistic expression, such a light qualities, unusual content, or unnatural viewer position, were eliminated. The photos were then examined to determine if the variables identified earlier in the literature were adequate to assess the scenic quality in the photographs. It was determined that all of these variables were helpful in assessing the scenic quality of most of the landscapes in the photos. However, there were a few scenes that contained scenic value that could not be adequately explained by these criteria. By looking at these scenes, five additional variables were identified as contributing to scenic quality. These elements, found in the landscape (i.e., content), should be included in the assessment of scenic viewsheds in Virginia:

- The scenic value of historic content (see Figure 3);
- The scenic value of human-influenced landscapes that include cultural content (see Figure 4);
- The scenic value of human-influenced landscapes that include urban content in scenic viewsheds (see Figure 5);
- The scenic value of ephemeral qualities (changing content in the landscape that is predictable and reasonably frequent) (see Figure 6).

Figure 3. Example of historic scenic content.

Figure 4. Example of human-influenced (cultural) scenic content.

Figure 5. Example of human-influenced (urban) scenic content.

Figure 6. Scenic value of ephemeral qualities or changing content that changes expectedly and occurs on reasonably frequent period of time such as flowers (**left**) and livestock (**right**). Figure on the right side shows the ephemeral content of Figure 4.

3.3. Guidelines for Scenic Viewshed Assessment Protocol

The following guidelines were used in developing the quantifiable assessment methodology:

- Concepts, variables, and measures should have a history of use that indicates a high degree of acceptance and credibility among scholars in this field;
- Variables and measures should be intuitively meaningful and make sense to those using them;

- Measurement scales should:
    - Be as straightforward and uncomplicated as possible (understandable);
    - Use descriptive interval scales when possible (meaningful distinctions for measurement);
    - Contain no more than seven intervals (seven is considered the number of categories most people can distinguish between [54]);
    - Not use mathematical functions other than addition and subtraction (reduce variability in measurement);
    - Be capable of easy disaggregation when combined mathematically (i.e., understand how the parts contribute to the final product).

Following these guidelines ensures that the proposed nomination and evaluation methodology is credible and that users will be able to apply it consistently and with minimal variation.

3.4. Variables for Scenic Quality and Public Concern or Sensitivity

The viewshed scenic quality assessment has two parts: The first is the scenic quality of the viewshed, and second is the public concern or sensitivity of the viewshed. In order to gain public support for the viewshed program, it was important that the viewsheds be those that the pubic were most concerned about.

The viewshed scenic quality variables are as follows:

- Viewshed size [1];
- Variety and visual complexity [52];
- Coherence and legibility [52,55];
- Presence of ephemeral content (see Figure 6) [1];
- Presence of positive human-influenced content [56];
- Incongruence or distraction (often man-made elements in a natural environment) [1].

The viewshed public concern or sensitivity variables are as follows:

- Demonstrated public concern or sensitivity [14];
- Number of viewers [57,58];
- Viewer activity [57,58];
- Landscape content [52];
- Historical and cultural significance features [14,52,58].

4. Scenic Viewshed Assessment Protocol

4.1. Check Sheets for Scenic Quality and Visual Concern/Sensitivity

A checklist was created to evaluate the scenic quality and visual concern/sensitivity of a viewshed. This checklist incorporates six variables for scenic quality and five for concern/sensitivity, all of which were derived from the literature review or the previously described scenic photo analysis. Each variable is rated on a three-point scale: high, moderate, or low. The checklist enables the assessment and scoring of each variable, which are then summed to provide a total viewshed score for both scenic quality and concern/sensitivity. The assessment process is illustrated using the viewshed shown in Figure 7. Figure 8 demonstrates that the landscape in Figure 9 has a high scenic quality, with a total scenic quality score of 7.

SCENIC VIEWSHED EVALUATION AND DESIGNATION FORM

VIEWSHED SCENIC QUALITY	HIGH	MODERATE	LOW
1. Viewshed Size *How wide is the view?*	panoramic [a] 3	medium view [b] 2	limited view [c] 1
2.Variety and Visual Complexity *How much variation in the visual characteistics of the landscape (patterns, color, form, line and textures)?*	High 2	Moderate 1	Low 0
3. Coherence and Legibility *How the visual composition fits together, and is distinct and memorable?*	High 2	Moderate 1	low 0
4. Ephemeral qualities in foreground and middle ground *Are ephemeral qualities a common content of the viewshed?*	frequent/ predictable 2	not frequent but predictable 1	not predictable 0
5. Positive human-influenced content in viewshed *positive, human-influenced content in the views*	Visual Striking 2	noticeable but not visual striking 1	not visible 0
6. Incongruent or distracting content in viewshed *Are incongruent elements (powerlines, mines, junkyards) visible in the viewshed?*	Highly visible -2	Visible [d] -1	not visible 0
TOTAL SCORE			
CLASS	**H: 11 ~ 7**	**M: 6 ~ 3**	**L: 2 ~ -1**

a. wide view and includes all distance zones
b. includes at least two distance, but not wide
c. one distance zone and narrow
d. visible, but surbordinate to visual elements and characteristics of the landscape

PUBLIC CONCERN OR SENSITIVITY	HIGH	MODERATE	LOW
1. Demonstrated the public awareness *Example: media articles, tourism guides, public meetings and gov. public relations*	Highly awareness 2	Moderate awareness 1	Low awareness 0
2. Number of viewers *Estimated number of people who see the viewshed*	seen over 100/day 3	seen over 100/week 2	seen under 100/week 1
3. Viewer activity *What people are doing when they view the landscape*	visible while recreating 2	visible from residents 1	visible while passing 0
4. Incongruent or distracting content not in viewshed but visible *Can powerlines, minings, junkyards be seen near the viewshed*	Highly visible -2	Visible -1	not visible 0
5. Historical and cultural features *Does the viewshed contain historical and cultural features*	National 3	State 2	Local 1
TOTAL SCORE			
CLASS	**H: 10 ~ 7**	**M: 6 ~ 3**	**L: 2 ~ 0**

SCENIC VIEWSHED DESIGNATION

Scenic viewshed designation is based on scenic quality and public concern
- *I = INCLUDE (designate as a Scenic Viewshed)*
- *SC = SPECIAL CONSIDERATION (designate as a Scenic Viewshed if other special considerations merit*
- *N = NOT INCLUDE (not designate as a Scenic Viewshed)*

VIEWSHED SCENIC QUALITY \ PUBLIC CONCERN OR SENSITIVITY	HIGH	MODERATE	LOW
HIGH	I	I	SC
MODERATE	SC	N	N
LOW	N	N	N

FINAL Viewshed DESIGNATION:

(See 'Definition of Terms' for additional information and literature related to each variable.)

Figure 7. Scenic viewshed evaluation and designation form.

VIEWSHED SCENIC QUALITY	HIGH	MODERATE	LOW
1. Viewshed Size *How wide is the view?*	panoramic [a] 3	medium view [b] 2	limited view [c] 1
2.Variety and Visual Complexity *How much variation in the visual characteistics of the landscape (patterns, color, form, line and textures)?*	High 2	Moderate 1	Low 0
3. Coherence and Legibility *How the visual composition fits together, and is distinct and memorable?*	High 2	Moderate 1	low 0
4. Natural Condition *How natural or undeveloped is the viewshed?*	natural/ undeveloped 2	scattered developed [d] 1	developed 0
5. Ephemeral qualities in foreground and middle ground *Are ephemeral qualities a common content of the viewshed?*	frequent/ predictable 2	not frequent but predictable 1	not predictable 0
6. Incongruent or distracting content in viewshed *Are incongruent elements (powerlines, mines, junkyards) visible in the viewshed?*	Highly visible -2	Visible [e] -1	not visible 0
TOTAL SCORE			
CLASS	**H: 11 ~ 7**	**M: 6 ~ 3**	**L: 2 ~ -1**

a. wide view and includes all distance zones
b. includes at least two distance, but not wide
c. one distance zone and narrow
d. scattered developed, but surordinate to natural characteristics of the landscape
e. visible, but surbordinate to visual elements and characteristics of the landscape

Figure 8. An example of assessing the "scenic quality" component of the viewshed in Figure 9. The sum of the scenic quality variables for this viewshed is 7, indicating that this this is a high-scenic-quality viewshed.

Figure 9. Depicts a Virginia viewshed used to demonstrate the viewshed scenic quality scoring (see Figure 8) and viewshed public concern scoring (see Figure 10).

PUBLIC CONCERN OR SENSITIVITY	HIGH	MODERATE	LOW
1. Demonstrated the public awareness *Example: media articles, tourism guides, public meetings and gov. public relations*	Highly awareness 2	Moderate awareness 1	Low awareness 0
2. Number of viewers *Estimated number of people who see the viewshed*	seen over 100/day 3	seen over 100/week 2	seen under 100/week 1
3. Viewer activity *What people are doing when they view the landscape*	visible while recreating 2	visible from residents 1	visible while passing 0
4. Incongruent or distracting content not in viewshed but visible *Can powerlines, minings, junkyards be seen near the viewshed*	Highly visible -2	Visible -1	not visible 0
5. Historical and cultural features *Does the viewshed contain historical and cultural features*	National 3	State 2	Local 1
TOTAL SCORE			
CLASS	H: 10 ~ 7	M: 6 ~ 3	L: 2 ~ 0

Figure 10. This figure is an example of the "public concern" assessment of the viewshed depicted in Figure 9. The sum of all the scored variables is 1, indicating a "low" sensitivity or concern score for the viewshed depicted in Figure 9.

4.2. Final Scenic Viewshed Designation

The scenic viewshed designation is determined by combining the scores for scenic quality and public concern (see Figure 11). A viewshed with a high scenic quality score and either a high or moderately high public concern score would be designated "include" on Scenic Virginia's Scenic Viewshed Register. Regardless of public concern, any viewshed with a low scenic quality score would not be designated inclusion in the Scenic Viewshed Register. Also, any viewshed with a moderate scenic quality score and either a moderate or low public concern score would not be included on the Scenic Viewshed Register.

SCENIC VIEWSHED DESIGNATION

Scenic viewshed designation is based on scenic quality and public concern

- *I = INCLUDE (designate as a Scenic Viewshed)*
- *SC = SPECIAL CONSIDERATION (designate as a Scenic Viewshed if other special considerations merit*
- *N = NOT INCLUDE (not designate as a Scenic Viewshed)*

VIEWSHED SCENIC QUALITY \ PUBLIC CONCERN OR SENSITIVITY	HIGH	MODERATE	LOW
HIGH	I	I	SC
MODERATE	SC	N	N
LOW	N	N	N

FINAL Viewshed DESIGNATION: Special consideration

Figure 11. Scenic Viewshed Final Designation Form.

There are two situations that deserve "special consideration". The first is when the viewshed has a high scenic quality score and a low public concern score, and the second is when a viewshed has a moderate scenic quality score and a high public concern score. A "special consideration" designation acknowledges that there may be unforeseen factors that should be considered in the designation. For example, in the first scenario, a viewshed may have only a moderate scenic quality score but also possess a unique sense of place and meaning to local people that are not fully reflected in the score and thus might require additional consideration before a designation decision can be made. In the second scenario, a viewshed may have a high scenic quality score but a low public concern score that requires additional consideration before making a decision. For example, the viewshed may have unique visual qualities or content that the scenic rating framework could not adequately consider and, therefore, merit consideration for designation, even though there is low public concern. This could include things such as an ephemeral factor that is unique or rare or a historical or cultural feature with exceptional significance, even at the local level.

4.3. Expert Review and Feedback

The viewshed assessment and designation protocol underwent two rounds of review by expert panels. The first review included seven members from the Scenic Virginia Viewshed Committee and eight experts, all professionals with extensive experience in scenic landscape issues. This group provided numerous valuable comments and suggestions to improve the clarity of the wording on the nomination and assessment forms.

The second review involved a different group of seven experts with professional experience in scenic landscape issues and five individuals from Scenic Virginia. This meeting focused on applying the viewshed assessment protocol to two distinctly different viewsheds, one of which included urban elements. They provided several minor recommendations, which were incorporated as minor revisions into the nomination and assessment protocol.

5. Pilot Evaluation with Experts

Using the derived evaluation method, four pilot tests were conducted between 2018 and 2019. Three of these tests took place in 2018. The first was conducted at the annual conference of the Virginia Chapter of the American Society of Landscape Architects in Virginia Beach, 2018, with 30 landscape architects. In this test, experts were briefed on the evaluation's purpose and methodology and were shown sample photographs before evaluating the views based on the viewshed assessment and designation. The second pilot test involved 20 science teachers working in Virginia. The same pilot test was later conducted at the VRS (Visual Resource Stewardship) conference with 80 experts in related fields. The pilot test conducted in 2019 took place at the VRS 2019 symposium, involving a total of 60 experts.

The VRS 2019 symposium, held in October of 2019, was an event for sharing research and project results on landscape resources. The Visual Resource Stewardship Conference was held at Argonne National Laboratory, Lemont, IL, with the theme "Seeking 20/20 Vision for Landscape Futures". Conference presentations addressed the following topics:

- Landscape scale and context;
- Visual resource benefits;
- Visual analysis methods;
- Integrated visual resource planning and application.

The educational content and evaluation methods were refined through these pilot tests. Below are the results of the most recent pilot test from the VRS 2019 symposium.

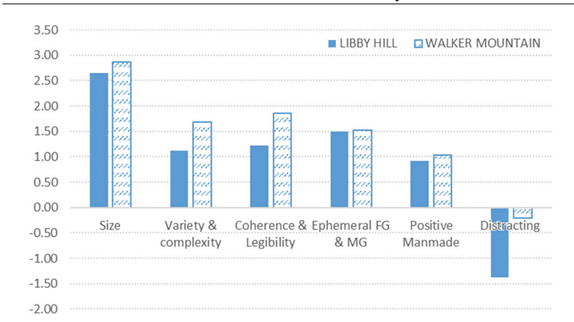
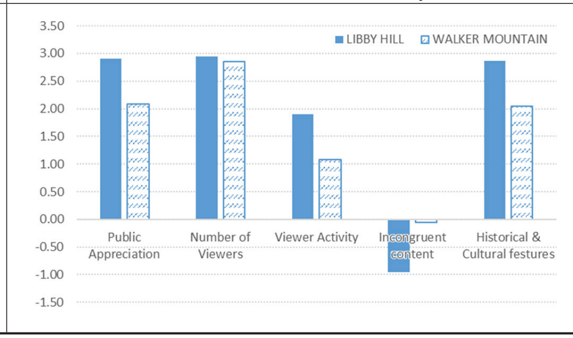
A total of 60 experts, including government officials and researchers, assessed Virginia's landscape resources, focusing on Libby Hill and Walker Mountain. These two viewsheds were selected because they represent different viewshed contexts. The viewpoint for Libby Hill is located in an urban context, and the viewpoint for Walker Mountain is in a rural area of Virginia. Figure 12 shows the photographs used during this pilot test. The Libby Hill viewshed is in Richmond, Virginia, and is sometimes referred to as the "view that made Richmond". It is a favorite viewpoint for many of those who live in Richmond. It does contain views of some developed areas in the valley below. The Walker Mountain viewshed is more typical of a rural Virginia landscape. The pilot test began with a brief introduction to the project and an explanation of the evaluation method, followed by separate assessments of Libby Hill and Walker Mountain. Participants were given ample time to individually evaluate Libby Hill after viewing its photograph. After the last expert completed their evaluation, the assessment of Walker Mountain proceeded similarly. Each landscape was assessed in less than 20 min.

Libby Hill	Walker Mountain
	

Figure 12. Photos of Libby Hill and Walker Mountain.

The evaluation results from the 60 participants were compiled as follows. For each component of viewshed scenic quality and public concern or sensitivity, averages were calculated and then summed. These summed averages formed the basis for determining the ranks of viewshed scenic quality and public concern or sensitivity. Based on these totals, viewshed scenic quality and public concern or sensitivity were ranked as high, moderate, or low. Finally, considering the ranks of each component, the overall importance of the landscape was determined. While Libby Hill received similar evaluations to Walker Mountain in the viewshed scenic quality component, it lost significant points in the distraction category. Libby Hill scored a total of 6.02 in viewshed scenic quality, ranking as moderate. In the public concern or sensitivity category, Libby Hill received higher scores than Walker Mountain but lost more points in the incongruent content category, as might be expected, because of the developed areas that were visible. Libby Hill's total average score of 9.67 in detailed categories ranked it as high in public concern or sensitivity (Table 4 and Figure 13). Overall, considering both categories' ranks, Libby Hill was classified as a landscape requiring special consideration (Table 5, left side) for inclusion on the Scenic Viewshed Register. Walker Mountain was similarly assessed in both categories. It received high scores in scale, diversity, and coherence and legibility in the viewshed scenic quality category, ranking high with a total score of 8.76. In public concern or sensitivity, it was also ranked high, with a total average of 8.03 (Table 4 and Figure 13). In summary, Walker Mountain was ranked high in both categories, receiving an "Include in the Scenic Viewshed Register" final rating. It would be considered among Virginia's special landscape resources (Table 5, right side) and requires no special consideration for inclusion on the register.

Table 4. Evaluation of Viewshed Scenic Quality and Public Concern or Sensitivity.

Viewshed Scenic Quality	Public Concern or Sensitivity
	

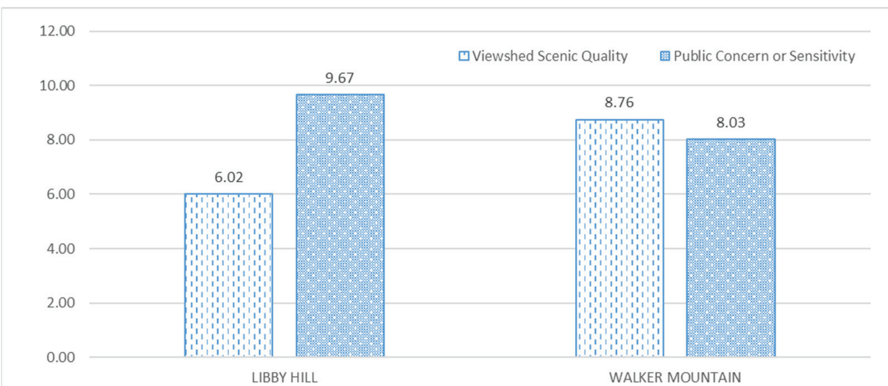


Figure 13. Total score of each category.

Table 5. Results of the pilot evaluation.

Libby Hill

category			Public Concern or Sensitivity		
	rank		High	Moderate	Low
		score	10~7	6~3	2~0
Viewshed Scenic Quality	High	11~7	I	I	SC
	Moderate	6~3	**SC**	N	N
	Low	2~-1	N	N	N

Result: Special Consideration

Walker Mountain

category			Public Concern or Sensitivity		
	rank		High	Moderate	Low
		score	10~7	6~3	2~0
Viewshed Scenic Quality	High	11~7	**I**	I	SC
	Moderate	6~3	SC	N	N
	Low	2~-1	N	N	N

Result: Include in Viewshed Register

The pilot test results showed that the experts quickly adapted to the evaluation method and provided relatively consistent assessments. This evaluation method demonstrated potential as a tool for identifying and managing scenic landscape resources in different areas.

6. Conclusions and Discussion

This project comprehensively outlines the essential requirements for establishing the Scenic Viewshed Register in Virginia, highlighting the crucial role that Scenic Virginia will undertake in fostering community involvement. By engaging Virginia's citizens in the identification process, the initiative empowers them to nominate viewsheds that they believe warrant recognition and conservation. This inclusive approach ensures that the register reflects the values and preferences of the local population, making it a truly community-driven effort. The critical steps taken include detailing the specific information necessary to engage the public effectively and identifying key variables for scenic quality assessment based on extensive literature reviews on scenic and visual assessments.

Clearly, there are some aspects of landscape experience that cannot be captured in a photograph, such as the sound of birds chirping, the smell of pine trees, and the cool feeling of a breeze. This is why the protocol developed as part of this study has two parts: a local citizen nomination and an expert assessment. Obviously, someone nominating a local viewshed would be familiar with and have experienced the viewshed firsthand. It is envisioned that the expert assessment would also involve first-hand experience of the landscape being assessed. Photographs of the landscape are required in the nomination process as well as a written description. This assures that the expert will be able to accurately locate and assess the viewshed being nominated. The assessment criteria developed as part of this project include ephemeral qualities, which could help in identifying experiential aspects of the landscape that may not be captured in a photograph. Photographs of different landscapes that were used to determine the assessment criteria derived from the literature review could capture visual characteristics of example landscapes. In this case, the landscapes were not being assessed. The photographs were conveying the visual characteristics of the landscape and not the experience of the landscape. Humans are very good at reading scenic characteristics from a photograph. People are used to looking at visual representations on television, newspapers, and books and answering simple questions about the visual characteristics

The use of photographs from the Scenic Virginia archive was crucial in validating and refining these variables. This meticulous selection process resulted in the creation of a comprehensive assessment protocol specifically designed to accurately evaluate the scenic value of Virginia's viewsheds. The protocol's objective is to methodically determine if a viewshed meets the criteria for inclusion in Scenic Virginia's Scenic Viewshed Register, considering both aesthetic attributes and public interest. This systematic approach ensures that each nominated viewshed is assessed through a transparent and repeatable process, building trust and credibility in the results.

There is now a greater public interest and a heightened need to protect our vital scenic viewsheds. We can learn from the pioneering landscape architects who developed visual resource management systems for public lands. However, to succeed, we must also embrace new methods of assessing scenic viewsheds that incorporate positive elements from human use, including historic landscape features, cultural patterns of human use, urban characteristics, and transient elements. As new concepts and methodologies for scenic assessment are developed, they must be empirically tested to ensure they align with what Virginians perceive as scenic. This is the next step.

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Back to the Village: Assessing the Effects of Naturalness, Landscape Types, and Landscape Elements on the Restorative Potential of Rural Landscapes

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Abstract: Rural landscapes are acknowledged for their potential to restore human health due to natural characteristics. However, modern rural development has degraded these environments, thereby diminishing the restorative potential of rural landscapes. Few studies have systematically analyzed the impact of naturalness, landscape types, and landscape elements on restorativeness using both subjective and objective measurements. This study investigated the restorative effects of various rural landscapes in Guangzhou, employing electroencephalography and eye-tracking technologies to record physiological responses and using the Restorative Components Scale and the Perceived Restorativeness and Naturalness Scale to evaluate psychological responses. The results indicated the following: (1) There was a significant positive correlation between perceived naturalness and restorativeness, surpassing the impact of actual naturalness. (2) Different landscape types had varying impacts on restorativeness at the same level of perceived naturalness. Natural forest landscapes, artificial forest landscapes, and settlement landscapes exhibited the most substantial restorative effects among the natural, semi-natural, and artificial landscapes examined, respectively. (3) Restorative properties varied across landscape elements: trees and water significantly enhanced restorativeness, whereas constructed elements reduced it. Findings from this study can provide support for policymakers to make informed decisions regarding the selection and arrangement of rural landscape types and elements to enhance mental health and well-being.

Keywords: rural landscape; mental restoration; naturalness; landscape type; landscape element

1. Introduction

1.1. Background

Rapid and intensive urbanization on a global scale not only leads to a monotonous, fast-paced lifestyle but also exacerbates human disconnection from nature and the fragmentation of rural ecological landscapes [1,2]. With increasing global attention to ecological, environmental protection and carbon neutrality issues, scholars have started researching the features and characteristics of rural settlement landscapes from perspectives such as landscape genetics, ecological environment, and landscape aesthetics, emphasizing the importance of restoring rural natural landscapes [3,4]. Numerous studies have indicated that exposure to natural environments, such as urban green spaces [5] and blue spaces [6], can reduce stress [7,8], increase happiness [9], and improve attention recovery [10], thereby offering psychological restorative benefits. These psychological benefits further improve human physiological health, such as by reducing blood pressure [11], lowering heart rate [12], and decreasing mortality from cardiovascular disease [13].

The Permanent European Conference for the Study of the Rural Landscape (PECSRL) identified that globalization, urbanization, and agricultural intensification are transforming our rural environment [14]. Due to construction delays, ecological degradation, and inadequate management, rural settlements face challenges such as lacking local distinctiveness and environmental degradation during development [15]. Rural areas not only serve as vital habitats for humans but also provide other functions, including cultural tourism, industrial development, and health restoration [16,17]. Consequently, it is crucial to conduct fundamental and applied research on current rural landscapes to provide new perspectives and strategies for managing landscapes to conserve ecosystems and sustain human health. Under the impetus of China's National Rural Revitalisation Strategy and Healthy China Strategy, the characteristics, main functions, and service targets of rural landscapes in China have undergone significant changes [18]. Modern rural areas are no longer expected to simply produce crops; instead, their resource advantages must be fully leveraged to develop functions such as agricultural production, economic development, and ecological conservation [19]. Thus, exploring the health benefits of rural landscapes is crucial for promoting public health. However, despite the backdrop of rapid urbanization, research on the potential of rural landscapes to alleviate stress, restore attention, and enhance well-being remains scarce.

1.2. Restorative Quality of Natural Environments and Naturalness

High-density rural development replaces natural environments and decreases opportunities for people to interact with nature, which is essential for promoting health [15]. Stress reduction theory (SRT) [20] and attention restoration theory (ART) [21] both emphasize the positive impact of natural environments on psychological health. ART posits that the unique environmental characteristics of nature help restore attention and relieve mental fatigue. In contrast, contact with artificial environments may deplete directed attention, leading to fatigue and irritability [22]. ART suggests that restorative environments contain four key elements: being away, extent, compatibility, and fascination [23]. SRT asserts that nature holds healing potential and that contact with nature reduces stress, thereby facilitating physiological recovery and providing psychological solace [24].

Naturalness is defined as the extent to which a landscape approximates its perceived natural state [25], and this concept is closely linked to the perceived quality of restorativeness [26]. For instance, a recent study indicated that parks with a high level of naturalness more effectively facilitate psychological recovery among visitors [20]. Another study investigating green and blue spaces revealed that more natural environments were correlated with increased positive emotions and, thus, had greater restorative qualities, whereas more artificial environments led to heightened anxiety and were considered less restorative [27]. Knez emphasized that urban green spaces with a higher level of naturalness promote stronger attachment emotions and cognitive engagement, resulting in enhanced well-being and therapeutic outcomes [28].

Naturalness can be further divided into perceived naturalness and actual naturalness [25]. Perceived naturalness is a subjective assessment based on an individual's response to the natural elements within a landscape [29]. Actual naturalness, on the other hand, is based on the intrinsic properties of a landscape and can be measured using scientific and quantitative methods [30]. The academic community has begun to quantify actual naturalness levels based on natural forms and structural integrity using landscape pattern metrics (such as patch size, edge effects, and connectivity) [31], remote sensing technologies, biotic indices, and landscape pattern indices [32], or more broadly in terms of vegetation cover and extent of aquatic elements [25]. Although there is currently no unified standard for measuring them, the concepts of actual and perceived naturalness provide a basis for the measurement standards used in this study.

1.3. Landscape Types and Elements of Perceived Restorativeness

Rural landscapes, which are distinguished by their unique ecological attributes and substantial restorative potential [33], are considered highly conducive to the restoration of physical and mental health in the modern world [34]. Studies have indicated that living in rural environments helps alleviate physiological stress such as tension and fatigue [35], improves emotional states, and facilitates psychological recovery [36]. For example, one study categorized rural landscapes into three types based on the level of human intervention, namely natural landscapes, productive landscapes, and artificial landscapes, and analyzed their effects on stress reduction [18]. Another study examined the effects of rural natural landscapes, agricultural landscapes, and cultural feature landscapes on place attachment and well-being [37]. These classifications not only demonstrate the diversity of research methods used but they also reveal a lack of uniformity in the categorization of rural landscapes. Moreover, few attempts have been made to develop a comprehensive classification system for rural landscapes that methodically investigates their restorative impacts from the perspective of matching naturalness with landscape type.

Some studies have examined the impact of certain landscape elements on restorativeness. For example, a recent study found that rural landscapes rich in natural elements significantly enhanced people's perception of healing [33]. Nordh noted that water, terrain, and vegetation are the most restorative elements in a landscape [38]. Another study analyzing the proportions of natural elements in scenes revealed that images with lower proportions of trees and higher proportions of sky and leaves helped to relieve stress [39]. Although the aforementioned studies compared the restorativeness of elements, research exploring the impact of rural landscape element combinations on perceived restorativeness, particularly across rural landscapes with varying degrees of naturalness, remains limited.

1.4. Objective, Subjective, and Reliable Measurement Tools

Most studies investigating the relationship between landscapes and perceived restorativeness have used psychological questionnaires [40]. However, some scholars have employed physiological measurement techniques such as heart rate variability (HRV) [41], blood pressure (BP) [42], skin conductance response (SCR) [5], electroencephalography (EEG) [43], and eye-tracking [44] to more scientifically and objectively verify the relationship between landscapes and perceived restorativeness. Among these measures, EEG most effectively reflects the degree of stimulation experienced by individuals, thus indicating their emotional changes in different landscape settings [45]. Brainwaves are typically classified into alpha (8–13 Hz), beta (14–30 Hz), theta (4–7 Hz), and delta (<4 Hz) waves. Alpha and beta waves are considered the most suitable indicators for stress assessment [46]. Alpha waves are associated with alertness, calmness, learning, and mental coordination; an increase in alpha wave values reflects a more relaxed, happy, and positive psychological state [47,48]. Depending on the frequency, alpha waves can be further divided into $\alpha 1$ (low frequency: 8–10 Hz) and $\alpha 2$ (high frequency: 10–13 Hz), with $\alpha 1$ waves associated with deep relaxation and a static psychological state, and $\alpha 2$ waves associated with a relaxed yet alert state [49]. Beta waves are usually associated with alertness, and a reduction in beta wave values indicates an increase in fatigue [50]. At 18 Hz, beta waves can be subdivided into $\beta 1$ (low frequency: 13–18 Hz) and $\beta 2$ (high frequency: 18–30 Hz), where $\beta 1$ waves represent a relaxed, focused, and coordinated mental state and $\beta 2$ waves represent an alert and excited state of tension [51]. Studies have used EEG to analyze the beneficial effects of blue spaces on mental health [6] to examine perceived fear in different types of nocturnal environments [52] and to confirm the restorative effects of various types of immersion in nature on youths experiencing stress [1].

Eye-tracking technology can record visual exploration patterns while observing a scene, and it can be used to capture various physiological data, such as heatmaps, average fixation duration, gaze path, pupil diameter, and blink rate [53]. In landscape research, these data are commonly used to assess the perceived restorative quality of and preferences for landscape scenes [54]. For instance, a recent study evaluated the restorative quality of various urban and rural scenes and conducted a detailed analysis of the differences in restorativeness among landscape elements in areas of interest (AOIs), finding that restorative scores for landscape scenes were positively correlated with average fixation duration and negatively correlated with the number of fixations [36]. Another study analyzed public spaces in rural landscapes and identified areas in different types of public space landscapes that attracted visual attention through an analysis of heatmap views generated via eye movements [55]. However, although studies of landscape restorativeness have increasingly adopted these objective measurement methods, research that conducts in-depth analyses of multiple physiological data alongside psychological scales, and particularly research that integrates qualitative and quantitative approaches, remains rare. Consequently, there is considerable scope for methodological innovation and comprehensive analysis in this field. By combining these methods, data can be captured from diverse perspectives, thereby facilitating a more comprehensive understanding of the research topic. Moreover, the use of both subjective and objective data allows for mutual validation, enhancing the reliability of the data and the validity of the study [56]. In this research, objective data reveal physiological changes, while subjective data provide insights into personal feelings and experiences. Together, these data streams provide a more detailed explanation of health status variations.

1.5. Study Aims

This study aimed to fill these research gaps and achieve the following objectives: (1) evaluate the restorative differences in rural landscapes of three levels of naturalness and explore the impact of perceived and actual naturalness on physical and mental health; (2) investigate the restorativeness of different types of landscapes with the same level of naturalness; and (3) analyze the relative restorative impact of various landscape elements in rural landscapes. Through this study, we aimed to provide sustainable development strategies for increasing the restorativeness of rural landscapes and strategically optimizing landscape configurations to enhance the restorative efficiency of existing rural landscapes.

2. Materials and Methods

2.1. Classification of Rural Landscapes

We employed a multi-tiered method of classifying rural landscapes based on international land use standards and relevant research [57] that has categorized rural landscapes by level of ecological naturalness (visual indicators: greenness, water bodies) into natural, semi-natural, and artificial landscapes.

This study selected the villages of Guangzhou City, Guangdong Province, China, as the research area. Guangzhou, located in the heart of the Guangdong–Hong Kong–Macao Greater Bay Area, is one of the fastest-developing cities in China. The rural areas of Guangzhou are characterized by their abundant soil and water resources, high population density, limited arable land, and superior natural environment [58]. However, rapid urbanization has led to extensive rural land development and changes in land use patterns, resulting in the continuous shrinkage of rural areas in Guangzhou. As a result, the diversity of Guangzhou's rural landscape types has diminished, the natural environment has been degraded, and the heterogeneities of the population, economy, and environmental quality in rural areas have become more pronounced [59]. Furthermore, rural construction activities in the Guangzhou area often prioritize policymakers' preferences or economic considerations. This neglects the local ecological and humanistic environment as well as the impact of the landscape on the health benefits of residents or tourists. Therefore, this study focused on evaluating the restorative quality of different rural landscape environments in Guangzhou. The aim was to provide a basis for improving the restorative construction of modern rural landscapes.

After conducting a detailed survey of rural landscapes in Guangzhou according to their level of naturalness [60], landscapes were categorized according to their functional and morphological characteristics as follows (Figure 1):

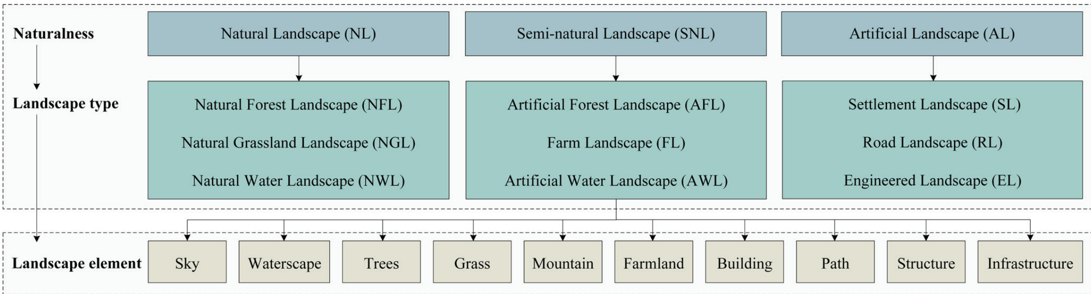


Figure 1. Classification of rural landscapes.

1. Natural Landscapes (NLs) are pristine and minimally disturbed landscapes featuring a variety of animal species, colors, and vegetation [22]. In rural areas of Guangzhou, these primarily include natural water landscapes (NWLs), natural forest landscapes (NFLs), and natural grassland landscapes (NGL) [18,36,61].
2. Semi-natural Landscapes (SNLs) are primarily transformed landscapes significantly influenced by human activities [61], including farm landscapes (FLs), artificial forest landscapes (AFLs), and artificial water landscapes (AWLs) [62].
3. Artificial Landscapes (ALs) are highly artificial landscapes created by human activities based on natural landscapes, mainly consisting of settlement landscapes (SLs), road landscapes (RLs), and engineered landscapes (ELs) [61,63,64].

2.2. *Selection of Experimental Images*

In this study, photographs were used to represent each rural landscape type. Multiple studies have confirmed that photographs can effectively substitute for on-site environmental surveys [5,44,65]. The selection of images for the experiment was completed through focus group interviews and expert evaluations [66]. Initially, three libraries of rural landscape photographs, each containing 200 images representing varying degrees of naturalness, were created. These photographs were taken on-site by two researchers in rural areas of Guangzhou, China, during clear weather conditions in December 2023, using a Sony A7 IV digital camera (provided by Sony, Tokyo, Japan). Subsequently, based on the objectives of the study, a focus group established the criteria for image selection and chose 12 photographs for each category of landscape. Nine experts, each with over 10 years of experience in environmental psychology and rural landscape design, were invited to rate the images based on the following criteria: (1) how accurately they reflected typical rural landscape scenes; (2) how prominently they displayed specific features of the landscape type; and (3) the inclusion of one image each of a large, medium, and small size for each landscape type. After aggregating the scores, the 9 highest-scoring images for each landscape type, giving a total of 81 images, were selected as the original stimuli for the study (Figure 2). Each image was adjusted to 1280 × 720 pixels with a resolution set at 300 DPI using Adobe Photoshop 2024.

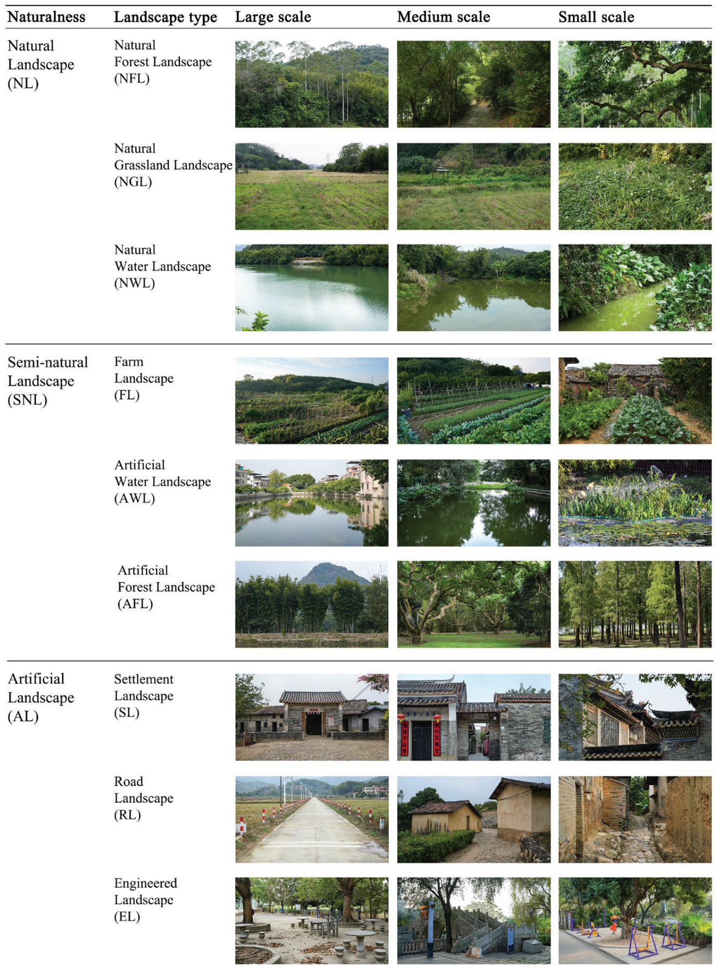


Figure 2. Examples of the experimental images of the different landscape types.

2.3. *Segmentation of Major Landscape Elements*

Image datasets such as Cityscapes, ADE20K, and SUN Database include detailed pixel-level annotations and they are, thus, widely used for the detection, classification, and segmentation of scenes to accurately determine the specific categories of each element in the images. In this study, we selected a semantic segmentation model pre-trained on the ADE20K dataset to perform semantic segmentation on experimental images. ADE20K offers 150 detailed categories of scene images [67], providing a broader selection of landscape element types than datasets such as Cityscapes. This enhances a model's accuracy and generalization capabilities, enabling high-quality image segmentation and the analysis of diverse and complex scenes [68,69]. To meet the requirements of this study, we adjusted the categorization model and finalized 10 landscape element categories: sky, waterscape, trees, grass, farmland, mountain, building, path, infrastructure, and structure. Of these, infrastructure is generally defined as the tangible constructions and assets that provide essential services to society, such as bridges and dams; meanwhile, structures refer to man-made buildings that do not possess, contain, or provide human habitation functions, such as towers and pavilions [70].

After conducting semantic segmentation on 81 experimental images, Python 3.7 was used to calculate the pixel proportion of each landscape element in the images and then to compute the quantitative landscape element index (Figure 3), which represents the percentage area of each landscape element in an image [36]. The specific implementation steps are shown in Algorithm 1. The equation for the landscape element index is as follows:

$$\text{Landscape Element Index} = \text{Number of pixels for element}/\text{Number of pixels in the overall image} \times 100\% \quad (1)$$

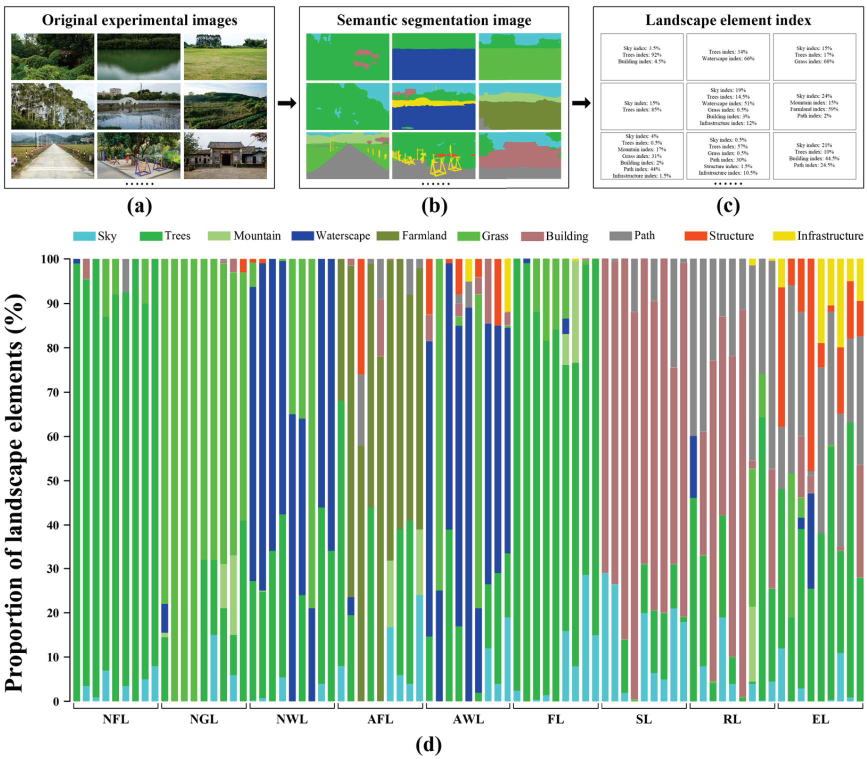


Figure 3. Semantic segmentation image and landscape element index. (**a**) Original experimental image; (**b**) semantic segmentation image; (**c**) landscape element index of one image; (**d**) percentage of typical landscape elements in each image of the different landscape types.

Algorithm 1: Experimental image processing algorithm

Input: Experimental image data **X**

Output: Landscape element index list **elementList**

model = SemanticSegmentation Model() // Initialize the semantic segmentation model

elementList = [] // Define an empty list to store the area percentages of various landscape elements

Y = model.process(X) // Apply the model to the experimental image to get segmented output

types = defineLandscapeElementTypes() // Define or retrieve the types of landscape elements

for element_type **in** types

colorSize = calculateElementSize(Y, element_type) // Calculate pixel size for the given landscape element type

allSize = X.size // Get the total pixel size of the experimental image

c_n = colorSize/allSize // Calculate the proportion of the landscape element

elementList.append(c_n) // Append the calculated index to the list

end for

return elementList // Return the list with indices of landscape elements

2.4. Participants

We used G*Power 3.1.9.4 to conduct a statistical power analysis to ensure an appropriate sample size [71]. For our comparative studies, we conducted our calculations using the F-test (analysis of variance [ANOVA]: repeated measures, within factors). The results indicated that a minimum sample size of 29 was required to achieve an effect size of 0.25, an α err prob of 0.05, a power of 0.80, one group, three measurements (three levels of naturalness or three landscape types at the same level of naturalness), and a sphericity correction of 0.5. To ensure satisfactory power, we adjusted the sample size to 40, achieving a power of 0.91.

Due to equipment and venue limitations, this study primarily included participants from the university community (students, teachers, and other school staff). We recruited participants from Guangzhou, China, using flyers and posters on university campuses, and via email and the social media platforms WeChat and Tencent QQ. The participants were required to have no physical or mental illnesses and to not be taking any medication. The participants were instructed to avoid smoking, alcohol consumption, and intense physical activity throughout the study period and to ensure sufficient sleep the night before the experiments, as these factors might affect the brainwave measurements [72]. Background information on the participants, including their gender, age, educational level, and permanent residence, was collected via a questionnaire. To increase the scientific rigor and applicability of the study results, we recruited 100 participants (50 urban and 50 rural residents) aged 18–58 years (M = 25, SD = 6.664). Among them, 40 participants from the South China University of Technology (20 males and 20 females) participated simultaneously in both physiological EEG and eye-tracking experiments. The descriptive information is shown in Table 1.

Table 1. Descriptive statistics of the socio-demographic backgrounds of the participants who underwent physiological measurements (N = 40).

Measures	Measure Types	*N*	%
Gender	Male	20	50
	Female	20	50
Age	18–23	20	50
	24–29	18	45
	30–35	2	5
Education	Undergraduate	13	32.5
	Master student	25	62.5
	Doctoral student	2	5
Permanent residence	City	25	62.5
	Village	15	37.5

2.5. Measurements

We collected data on the differences in visual stimuli effects across three levels of naturalness, nine landscape types, and 10 landscape elements using physiological measurements (EEG, eye-tracking) and psychological assessments (RCS, PRNS).

2.5.1. Psychological Measurements

1. RCS

We used the Restorative Components Scale (RCS), proposed by Laumann [68], to assess the extent to which contact with specific environments facilitated psychological health recovery. The RCS is based on ART and includes 22 items divided into four theoretical dimensions: being away, extent, fascination, and compatibility (Table A1) [73]. All of the items have been accurately translated from English into Chinese in previous studies and are rated using a 5-point Likert scale ranging from 1 to 5 [6,33]. In this study, the participants rated each type of landscape. The overall perceived restorativeness score for each landscape was then determined by calculating the average scores across the four dimensions for all participants. The higher the score, the more significant the landscape's role in promoting psychological health.

2. PRNS

The Perceived Restorativeness and Naturalness Scale (PRNS) was designed to separately assess potential restorativeness using a rating system that ranges from 1 to 7 (Table A2). Raters score each image based on personal experience, where a score of 1 represents the lowest evaluation (e.g., an extremely low restorative quality) and a score of 7 indicates the highest evaluation (e.g., an extremely high restorative quality). The PRNS can also be used to assess perceived naturalness, with 1 representing an extremely low level of naturalness and 7 representing an extremely high level of naturalness. This evaluation system effectively quantifies individuals' subjective perceptions of images and analyzes the relationship between image characteristics and perceptions [50].

Given the large number of image samples involved in this study, to avoid the complexity of using the RCS for individual image restorativeness scoring, the participants were only required to give ratings based on their overall impression of the nine types of landscapes using the RCS and to use the PRNS to score the 81 specific images for restorativeness. Before conducting statistical analysis, the RCS and PRNS data had to pass the reliability analysis. Cronbach's alpha coefficient was used to assess the internal consistency of the scales [33], with higher values indicating better consistency. Specifically, a Cronbach's alpha coefficient above 0.800 indicates good internal reliability [74].

2.5.2. Physiological Measurements

1. EEG

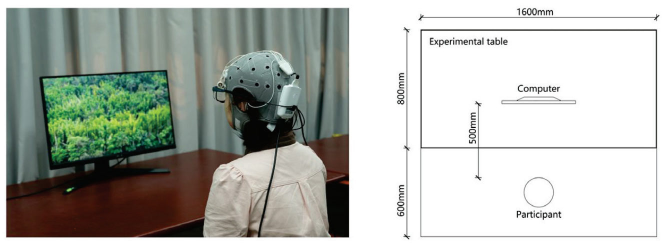
We used a wireless EEG system (model NE Enobio 8, from Neuroelectrics, Barcelona, Spain) and its accompanying software to collect the EEG data. An electrode cap was worn by the participants according to the international standard 10–20 system, recording brainwaves from the forehead above the eyes (at the FP1 and FP2 positions). The FP1 and FP2 positions are located in the frontal lobe area, which plays a key role in processing emotions and stress responses. Before the participants viewed the scene images, we recorded 1 min of EEG data from a blank scene as a baseline [75]. When switching between scenes, we input event markers to segment the subsequent EEG data. The EEG data were recorded in real-time (at a rate of 512 Hz). The output raw EEG signals were preprocessed using the Matlab-based EEGLAB toolbox (version 14.0.0). EEGLAB is widely used by researchers for processing continuous EEG recordings [76,77]. In this process, the EEG signals were referenced to the average value for the bilateral mastoids, and artifacts such as electrooculographic and electromyographic interferences were removed through independent component analysis [78]. The EEG signals were then segmented for each participant in the corresponding scenes. To quantify the EEG signals, we used the Letswave toolbox to extract the frequency domain features. The logarithmic power values of the $\alpha1$, $\alpha2$, $\beta1$, and $\beta2$ waves were extracted as defined in the EEG power spectrum [79] to obtain the quantified EEG metrics required.

2. Eye-tracking

The aSee Glasses eye-tracking analysis system (provided by 7Invensun, Beijing, China) was used to collect eye movement data from an infrared pupil camera at a rate of 120 Hz. Post-experiment, the accompanying software, aSee Studio, was used for AOI segmentation and data analysis, and the data were subsequently exported as average fixation duration and visual attention heatmaps.

2.6. Experimental Procedure

The experiments were conducted between 18 and 27 December 2023 in a laboratory at the South China University of Technology. All of the participants undertook the experiments under the same conditions, including room setup, temperature, and lighting. Three research members conducted the experiments on each participant during the periods from 9:30 to 11:30 AM and from 2:00 to 5:30 PM (Figure 4).



(a) **(b)**

Figure 4. Environment and arrangement of the experiment. (**a**) Field experimental environment; (**b**) laboratory floor plan.

The researchers first described the standard procedures of the experiment to the participants, acquainted them with the experimental equipment, and informed them of their rights before asking them to sign the informed consent form. After giving their consent to participate, the participants reported their age, gender, educational level, and permanent residence in the background survey questionnaire (Table 1). We then explained the RCS and PRNS and helped the participants properly put on and test the EEG and eye-tracking devices. The participants were then led to a computer displaying images and were informed that they could freely view the scenes during the experiment but must avoid significant head movements. After a five-minute break, each participant was randomly assigned a sequence of images of equal naturalness and three different landscape types. The image slideshow included a minute of blank screen followed by 9 min of images (each image lasted 15 s, with each landscape type displayed for 3 min). Before playing each landscape type, a white screen with text prompts was displayed for 3 s. The EEG and eye movement data were continuously recorded during the experiment. After viewing the slides, participants were given a short period to reflect on the differences among the three types of landscapes under the same level of naturalness. They then filled out the RCS for each landscape type, guided by corresponding sample images provided in the PRNS. This method not only enabled participants to conduct a more comprehensive comparison among three levels of naturalness and three types of landscapes within the same naturalness level but also ensured the accuracy and reliability of the collected data. After filling out the RCS, participants took a five-minute break and then repeated the process twice more with slides of two other levels of naturalness. Upon the final round of slides, the participants completed the PRNS. The entire experiment lasted approximately 60 min per participant (Figure 5).

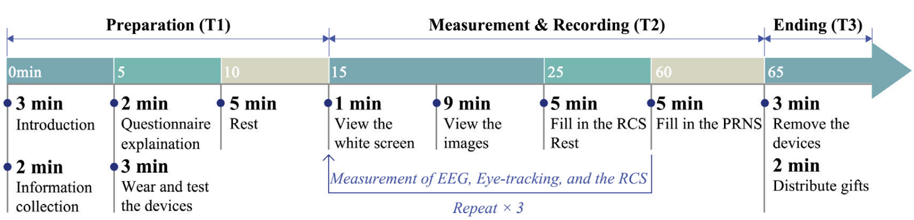


Figure 5. Experimental procedure.

2.7. Statistical Analysis

Initially, repeated measures ANOVA was used to calculate the averages of the EEG ($\alpha 1$, $\alpha 2$, $\beta 1$, and $\beta 2$), RCS, and eye-tracking data (average fixation duration on different elements). If significant correlations were identified, further pairwise comparisons were conducted using the least significant difference (LSD) post hoc test. Subsequently, the Friedman test was employed to analyze the PRNS data, and the Wilcoxon signed-rank test was used to analyze the differences in correlations between perceived naturalness and actual naturalness. Next, general linear regression analysis was applied to explore the relationship between the landscape element indices and restorativeness. Lastly, linear regression analysis was used to compare the impact of perceived and actual naturalness on restorativeness to identify which types of naturalness played the most important roles. All of the statistical analyses were conducted using IBM SPSS Statistics 27 and Microsoft Excel 2021, with statistical significance set at $p < 0.05$.

3. Results

The analysis of the results for the psychological and physiological dimensions is presented in four parts. First, the results of the repeated measures ANOVA for restorativeness using the RCS across different levels of naturalness and types of landscapes are reported. Second, we report a simple linear regression analysis conducted on the PRNS data to reveal the impact of different factors and levels of naturalness on restorativeness. Third, the consistency of the link between the EEG data on restorativeness across different levels of naturalness using repeated measures ANOVA is reported. Finally, a detailed assessment of restorativeness from both a quantitative perspective and a qualitative perspective using the eye-tracking data (average fixation duration and visual attention heatmaps) is conducted.

3.1. RCS Results

3.1.1. Internal Consistency and Correlation

In this study, the overall Cronbach's alpha value for the RCS was 0.943, with the scores being 0.907 for the being away dimension, 0.905 for the extent dimension, 0.930 for the fascination dimension, and 0.819 for the compatibility dimension. These results indicate high consistency among the four dimensions of the RCS. A further correlational analysis (Table 2) revealed that the four dimensions were closely correlated with the total score (Pearson = 0.632–0.893) and highly correlated with each other (Pearson = 0.346–0.690), with all correlations being statistically significant ($p < 0.001$).

Table 2. Pearson correlation matrix for the RCS data.

	1	**2**	**3**	**4**	**5**
1 Being Away	1				
2 Extent	0.647 ***	1			
3 Fascination	0.690 ***	0.682 ***	1		
4 Compatibility	0.346 ***	0.396 ***	0.461 ***	1	
5 Overall restorative quality	0.870 ***	0.822 ***	0.893 ***	0.632 ***	1

*** $p < 0.001$.

3.1.2. Relationship of Naturalness on Perceived Restorativeness

The RCS results indicated significant differences in perceived restorativeness among the three levels of naturalness of the landscapes (Figure 6, Table A3), with natural landscapes (3.758 ± 0.472) having the highest perceived restorativeness, followed by semi-natural landscapes (3.516 ± 0.497), and then artificial landscapes (2.923 ± 0.598), $F_{(1.671, 165.429)} = 107.046$, $p < 0.001$. Further LSD post hoc tests revealed that the restorativeness of the natural landscapes was significantly greater than that of the semi-natural landscapes (M_{NL}-M_{SNL} = 0.242, $p < 0.001$) and the artificial landscapes (M_{NL}-M_{AL} = 0.835, $p < 0.001$); likewise, the restorativeness of the semi-natural landscapes was significantly greater than that of the artificial landscapes (M_{SNL}-M_{AL} = 0.593, $p < 0.001$).

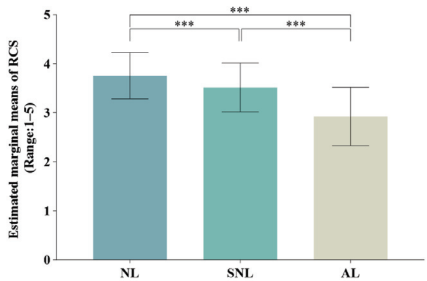


Figure 6. One-way repeated measures ANOVA and post hoc (LSD) pairwise comparisons of the overall RCS scores across three degrees of naturalness; $N = 40$; mean ± SD; *** $p < 0.001$.

3.1.3. Relationship of Landscape Type on Perceived Restorativeness

The results of analyzing the RCS scores for the rural landscape types with different levels of naturalness are shown in Figure 7 (Table A4). Significant differences were observed in the RCS scores among the three natural landscape types, with restorativeness scores ranked from highest to lowest as follows: natural forest landscapes (3.940 ± 0.542), natural water landscapes (3.784 ± 0.622), and natural grassland landscapes (3.550 ± 0.566), $F_{(1.872, 185.340)} = 23.127$, $p < 0.001$. The LSD post hoc tests showed a significant difference between natural forest and natural water landscapes (M_{NFL}-M_{NWL} = 0.156, $p = 0.002 < 0.01$); natural forest landscapes had significantly higher scores than natural grassland landscapes (M_{NFL}-M_{NGL} = 0.390, $p < 0.001$) and natural water landscapes had significantly higher scores than grassland landscapes (M_{NWL}-M_{NGL} = 0.234, $p \leq 0.001$).

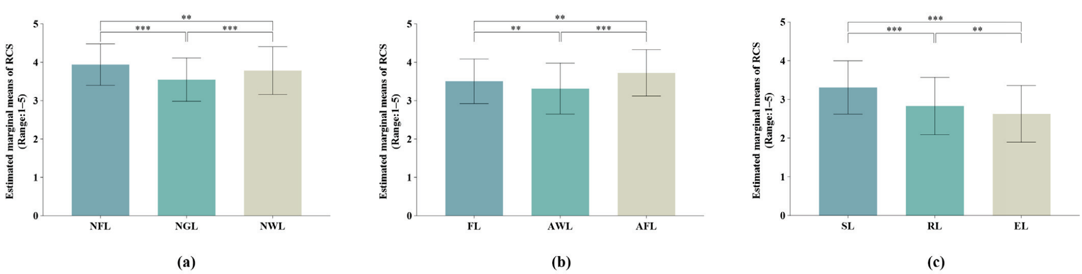


Figure 7. One-way repeated measures ANOVA and post hoc (LSD) pairwise comparisons of the RCS scores; $N = 40$; mean ± SD; ** $p < 0.01$; *** $p < 0.001$. (**a**) Natural landscape. (**b**) Semi-natural landscape. (**c**) Artificial landscape.

Significant differences were also observed among the semi-natural landscapes, $F_{(2,198)} = 21.172$, $p < 0.001$, with artificial forest landscapes (3.727 ± 0.605) having a significantly higher restorative potential than farm landscapes (3.506 ± 0.578) and artificial water landscapes (3.316 ± 0.665). The LSD post hoc tests revealed a significant difference between artificial forest and artificial water landscapes (M_{AFL}-M_{AWL} = 0.411, $p < 0.001$), with the restorative potential of farm landscapes being lower than that of artificial forests (M_{FL}-M_{AFL} = −0.222, $p = 0.001 < 0.01$). Artificial water landscapes had significantly lower scores than farm landscapes (M_{AWL}-M_{FL} = −190, $p = 0.003 < 0.01$).

For artificial landscapes, the RCS results showed significant differences among the three types, $F_{(2,198)} = 50.102$, $p < 0.001$. Settlement landscapes (3.310 ± 0.689) were considered the most restorative among the artificial types, followed by road landscapes (2.832 ± 0.741) and engineered landscapes (2.628 ± 0.733). Pairwise comparisons indicated that settlement landscapes had significantly higher scores than road landscapes (M_{SL}-M_{RL} = 0.478, $p < 0.001$) and engineered landscapes (M_{SL}-M_{EL} = 0.682, $p < 0.001$), with a highly significant difference between road and engineered landscapes (M_{RL}-M_{EL} = 0.204, $p = 0.005 < 0.01$).

3.1.4. Relationship of Permanent Residence on Perceived Restorativeness

To observe whether there were differences in perceived restorativeness among the participants from rural and urban locations, we conducted an independent samples t-test on the participants' permanent residences. The results showed a significant correlation between permanent residence and perceived restorativeness ($p < 0.001$). For both the overall scores and the scores for different naturalness levels of rural landscapes, the participants from urban areas generally gave higher perceived restorativeness scores than the participants from rural areas (Table 3).

Table 3. Effects of the participants' permanent residences on perceived restorativeness.

Naturalness	City (Mean ± SD)	Rural (Mean ± SD)	t	*p*	CI
Whole	3.602 ± 0.354	3.197 ± 0.341	5.832	<0.001 ***	0.267; 0.543
NL	3.930 ± 0.376	3.586 ± 0.499	3.892	<0.001 ***	0.168; 0.519
SNL	3.736 ± 0.468	3.296 ± 0.426	4.918	<0.001 ***	0.263; 0.618
AL	3.139 ± 0.570	2.708 ± 0.550	3.850	<0.001 ***	0.209; 0.653

CI is the 95% confidence interval of the difference in the means between city and rural residents. *** $p < 0.001$.

3.2. PRNS Results

The PRNS was used to evaluate the rural landscape images along two dimensions: perceived restorativeness and perceived naturalness. The scale demonstrated high internal consistency in both dimensions, with stable reliability indicated by Cronbach's alpha coefficients of 0.850 for the perceived restorativeness dimension and 0.841 for the perceived naturalness dimension. The restorativeness assessment results from the PRNS were also consistent with those from the RCS, suggesting that the two scales complement each other in conducting an in-depth exploration of the impact of landscape elements and perceived naturalness on perceived restorativeness.

3.2.1. Impact of Perceived and Actual Naturalness on Perceived Restorativeness

Naturalness can be divided into perceived naturalness and actual naturalness. In this study, the naturalness results from the PRNS were used as the indicator of perceived naturalness, and the sum of the indices for landscape elements such as trees, mountains, farmland, waterscapes, and glass in the semantic segmented images was used to determine actual naturalness. A Wilcoxon signed-rank test revealed significant consistency between the perceived naturalness and actual naturalness results ($p < 0.001$). On this basis, a multiple regression model was constructed to explore the extent to which both factors influenced perceived restorativeness. The results showed that perceived restorativeness had a significant positive correlation with perceived naturalness ($p < 0.001$). The regression equation was as follows:

$$\text{perceived restorativeness} = 2.249 + 0.564 \times \text{perceived naturalness} \tag{2}$$

In summary, although there was some correlation between perceived and actual naturalness, the main factor affecting perceived restorativeness was the level of perceived naturalness (Table 4).

Table 4. Effects of perceived and actual naturalness on perceived restorativeness.

Naturalness	B	Beta	t	*p*	VIF	R^2	Adjusted R^2
(Constant)	2.249	/	14.487	<0.001 ***	/		
Perceived	0.564	0.913	10.772	<0.001 ***	2.509	0.777	0.771
Actual	−0.095	−0.041	−0.488	0.627	2.509		

B is the unstandardized coefficients, Beta is the standardized coefficients, and VIF is the collinearity statistics. *** $p < 0.001$.

3.2.2. Impact of Different Landscape Elements on Perceived Restorativeness

We used semantic segmentation to classify the images in the study into 10 landscape element indices ($N = 81$) and employed multiple regression analysis to determine the correlation between different landscape elements and perceived restorativeness. For rural landscapes overall, perceived restorativeness indicated that an increase in the proportion of trees or a decrease in the proportion of buildings, paths, and structures enhanced the perceived restorativeness of the rural landscape type (Table 5). The regression equation was as follows:

$$\text{perceived restorativeness} = 4.787 + 0.011 \times \text{tree} - 0.009 \times \text{building} - 0.024 \times \text{path} - 0.023 \times \text{structure} \quad (3)$$

Table 5. Relationship between different landscape elements and the overall PRNS perceived restorativeness scores.

Element	B	Beta	t	p	VIF	R^2	Adjusted R^2
(Constant)	4.787	/	25.420	<0.001 ***	/	0.628	0.581
Sky	0.002	0.019	0.232	0.818	1.228		
Trees	0.006	0.260	2.602	0.011 *	1.909		
Mountain	−0.023	−0.130	−1.613	0.111	1.251		
Waterscape	0.004	0.114	1.202	0.233	1.711		
Farmland	0.000	−0.005	−0.056	0.955	1.326		
Building	−0.009	−0.309	−3.024	0.003 **	1.997		
Path	−0.024	−0.401	−4.526	<0.001 ***	1.503		
Structure	−0.023	−0.226	−2.907	0.005 **	1.150		
Infrastructure	−0.027	−0.122	−1.436	0.155	1.378		
Grass				*N*			

B is the unstandardized coefficients, Beta is the standardized coefficients, and VIF is the collinearity statistics. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Increasing the proportion of sky and waterscape or reducing the proportion of mountains and infrastructure elements also helped to enhance restorativeness, although these effects did not reach statistical significance.

The multiple regression analysis of each level of naturalness showed that for the natural landscapes ($N = 27$), a decrease in the proportion of grass increased the restorativeness, whereas for the semi-natural landscapes ($N = 27$), a decrease in the proportion of waterscape and farm increased the restorativeness (Table 6).

Table 6. Relationship between landscape elements and the PRNS perceived restorativeness scores across different levels of naturalness.

Naturalness	Element	B	Beta	t	p	VIF	R^2	Adjusted R^2
NL	(Constant)	5.537	/	34.466	<0.001 ***	/	0.511	0.331
	Grass	−0.008	−0.700	−3.613	0.002	1.461		
SNL	(Constant)	5.536	/	26.409	<0.001 ***	/	0.538	0.293
	Waterscape	−0.019	−0.947	−2.947	0.009	3.799		
	Farmland	−0.012	−0.610	−2.672	0.016	1.919		
AL					*N*			

B is the unstandardized coefficients, Beta is the standardized coefficients, and VIF is the collinearity statistics. *** $p < 0.001$.

3.3. EEG Results

The EEG data (α1, α2, β1, and β2) under exposure to rural landscapes with different levels of naturalness levels were compared, and the relationship between naturalness and restorativeness on a physiological level was explored using one-way repeated measures ANOVA. The results showed significant differences in the values of α1, α2, β1, and β2 under the three categories of naturalness after 9 min of exposure to landscapes of varying naturalness (Table A5).

3.3.1. Alpha Wave Response to Restorativeness

Exposure to the three levels of naturalness resulted in significant differences in $\alpha 1$ values (Figure 8), $F_{(1.662, 64.813)} = 4.737$, $p = 0.017 < 0.05$. The results indicated that viewing natural landscapes (0.015 ± 0.523) led to higher $\alpha 1$ values than viewing semi-natural (-0.134 ± 0.435) and artificial landscapes (-0.148 ± 0.477), and, thus, natural landscapes possessed greater restorative potential. Pairwise comparisons revealed significant differences between natural and semi-natural landscapes (M_{NL}-$M_{NSL} = 0.149$, $p = 0.042 < 0.05$), with natural landscapes generating significantly higher $\alpha 1$ values than artificial landscapes (M_{NL}-$M_{AL} = 0.163$, $p = 0.004 < 0.01$). Although the difference in $\alpha 1$ values between the semi-natural and artificial landscapes was not significant, the comparative means showed that the semi-natural landscapes had a higher restorativeness than the artificial landscapes.

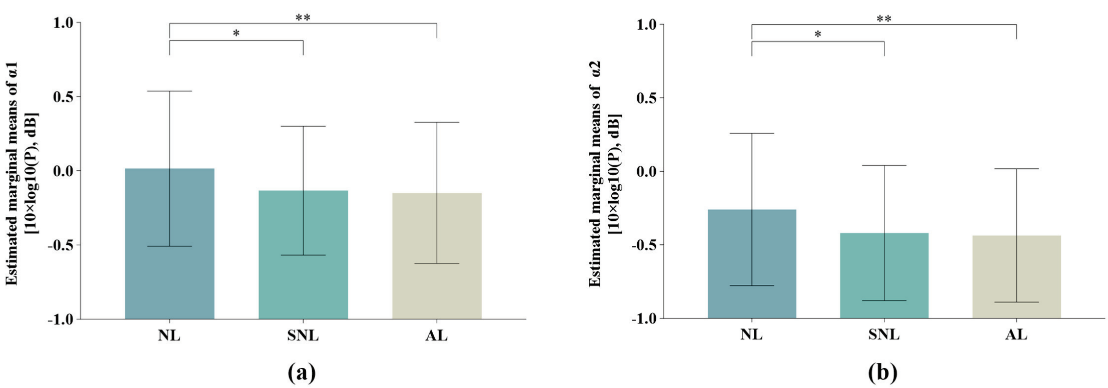


Figure 8. One-way repeated measures ANOVA and post hoc (LSD) pairwise comparisons of α waves in response to landscapes with different levels of naturalness; $N = 40$; mean $\pm$ SD; * $p < 0.05$; ** $p < 0.01$. (**a**) $\alpha 1$. (**b**) $\alpha 2$.

Significant differences in $\alpha 2$ values were also found across different levels of naturalness, $F_{(2, 78)} = 5.107$, $p = 0.008 < 0.01$. Viewing natural landscapes resulted in the highest $\alpha 2$ values (-0.258 ± 0.519), and these were significantly higher than the values when viewing semi-natural landscapes (-0.420 ± 0.461, M_{NL}-$M_{NSL} = 0.162$, $p = 0.026 < 0.05$) and artificial landscapes (-0.436 ± 0.454, M_{NL}-$M_{AL} = 0.177$, $p = 0.002 < 0.01$).

3.3.2. Beta Wave Responses to Restorativeness

Significant differences were observed in the $\beta 1$ waves across the different levels of naturalness (Figure 9), $F_{(1.736, 67.709)} = 5.991$, $p = 0.006 < 0.01$. Post hoc LSD comparisons revealed the following rankings for the $\beta 1$ data: natural landscapes (-0.444 ± 0.509), semi-natural landscapes (-0.590 ± 0.483), and artificial landscapes (-0.638 ± 0.440). No significant difference was found between the semi-natural and artificial landscapes, but moderately significant differences were identified for the $\beta 1$ wave values between the natural and semi-natural landscapes (M_{NL}-$M_{SNL} = 0.146$, $p = 0.035 < 0.05$), and the natural landscapes resulted in significantly higher $\beta 1$ wave values than the artificial landscapes (M_{NL}-$M_{AL} = 0.194$, $p < 0.001$).

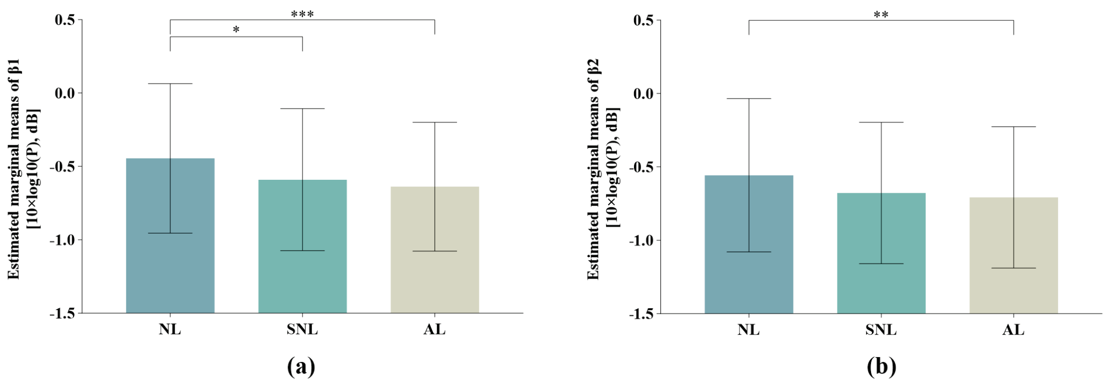


Figure 9. One-way repeated measures ANOVA and post hoc (LSD) pairwise comparisons of β1 waves in response to landscapes with different levels of naturalness; $N = 40$; mean ± SD; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$. (**a**) β1. (**b**) β2.

In terms of β2 waves, different levels of naturalness in rural landscapes had different impacts, $F_{(1.642,\ 64.030)} = 4.338$, $p = 0.023 < 0.05$. Compared with the natural (−0.558 ± 0.522) and semi-natural landscapes (−0.678 ± 0.481), the artificial landscapes (−0.709 ± 0.482) generated the lowest β2 values, with a moderately significant difference from the natural landscapes (M_{NL}-M_{AL} = 0.151, $p = 0.001 < 0.01$).

3.4. Eye-Tracking Results

3.4.1. Average Fixation Duration Responses to Perceived Restorativeness

Eye movement analysis was conducted to provide deeper insights into perceived restorativeness [80], with an increase in average fixation duration associated with a higher perceived restorative quality [81]. To further substantiate the previously reported perceived restorativeness results, we measured the average fixation durations within AOI in the images across varying levels of naturalness, landscape types, and landscape elements.

Average fixation durations were calculated for each participant and averaged across images for each level of naturalness and landscape type. Although the differences in average fixation duration were not statistically significant, comparing the means still allowed a rough assessment of the differences in restorativeness based on this measure (Table 7). The average fixation duration rankings from highest to lowest were as follows: natural landscapes (0.493 ± 0.152), semi-natural landscapes (0.482 ± 0.138), and artificial landscapes (0.477 ± 0.130). Differences were also evident between the different types of landscapes: within the natural landscapes, the longest average fixation duration was seen in natural forest landscapes (0.517 ± 0.201), followed by natural water landscapes (0.483 ± 0.165), and then natural grassland landscapes (0.479 ± 0.127); within the semi-natural landscapes, the artificial water landscapes (0.473 ± 0.144) elicited shorter average fixation durations than the farm landscapes (0.482 ± 0.149) and artificial forest landscapes (0.491 ± 0.159); and among the artificial landscapes, the average fixation durations were higher for settlement landscapes (0.485 ± 0.133) than for road landscapes (0.479 ± 0.134) or engineered landscapes (0.466 ± 0.142).

Table 7. Comparison of average fixation duration (s) in different landscapes.

	NL	SNL	AL	NFL	NGL	NWL	FL	AWL	AFL	SL	EL	RL
M	0.493	0.482	0.477	0.517	0.479	0.483	0.482	0.473	0.491	0.485	0.466	0.479
SD	0.152	0.138	0.130	0.201	0.127	0.165	0.149	0.144	0.159	0.133	0.142	0.134

Using image data processed with semantic segmentation technology, we subdivided the images into different landscape element AOIs and calculated the average fixation duration for each landscape element. After verifying the numerical signs and normality of these data, we conducted a one-way repeated measures ANOVA and post hoc LSD tests. The results showed significant differences in average fixation durations among the different landscape elements, $F_{(6.034, 235.330)} = 13.924$, $p < 0.001$ (Table A6), with average values ranked in descending order as follows (Figure 10): trees (0.503 ± 0.144), grass (0.498 ± 0.129), farmland (0.488 ± 0.112), waterscape (0.487 ± 0.140), building (0.471 ± 0.100), path (0.469 ± 0.120), infrastructure (0.456 ± 0.096), structure (0.427 ± 0.077), mountain (0.402 ± 0.113), and sky (0.349 ± 0.007). Comparisons of the average fixation durations further revealed differences in restorativeness among the different landscape elements.

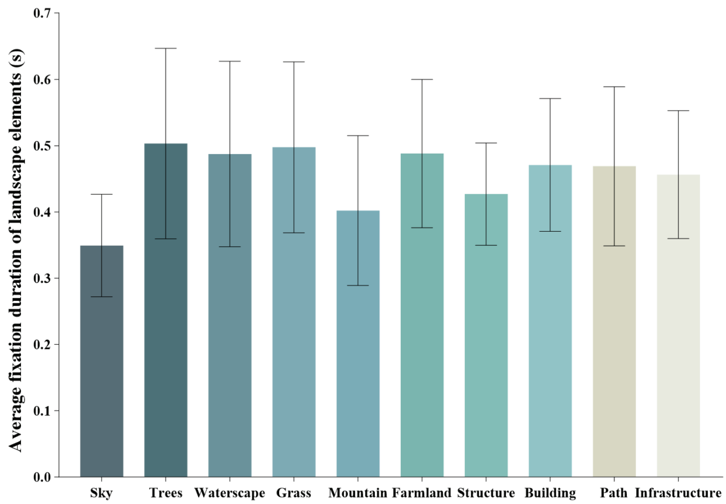


Figure 10. One-way repeated measures ANOVA comparisons of average fixation durations for different landscape elements. $N = 40$; mean ± SD.

The pairwise comparison results for the different landscape elements are shown in Figure 11. Overall, trees elicited the highest average fixation duration, and the result was significantly different from those for mountain ($p < 0.001$) and structure ($p < 0.001$). Sky elicited the lowest average fixation duration, possibly due to receiving less attention than the other elements. Natural landscape elements elicited higher average fixation durations than the artificial elements, as exemplified by grass eliciting higher durations than infrastructure ($p = 0.022 < 0.05$).

Among the natural landscape elements, trees had a significantly higher average fixation duration than grass, which is consistent with the previous finding that natural forest landscapes are more restorative than natural grassland landscapes [50]. In addition, nearer natural elements had higher average fixation durations than distant ones; for example, trees had higher durations than mountains ($p < 0.001$).

Among the artificial landscape elements, buildings attracted the highest average fixation duration. Structures had the lowest average fixation duration, showing significant differences in restorativeness compared to other artificial elements. For example, the building had a significantly greater average fixation duration than the structure ($p < 0.001$).

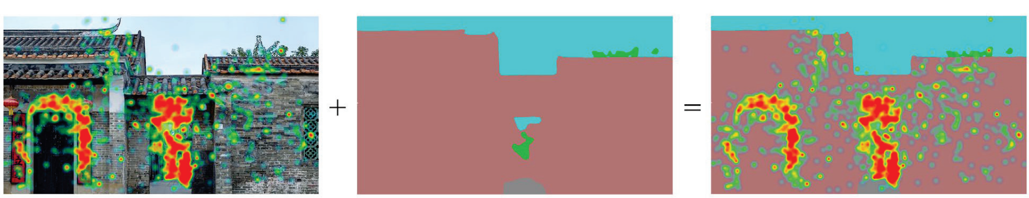
	Sky	Trees	Grass	Waterscape	Mountain	Farmland	Path	Building	Infrastructure	Structure
Sky	—	***	***	***	**	***	***	***	***	***
Trees	<0.001	—	/	/	***	/	/	*	*	***
Grass	<0.001	0.753	—	/	***	/	/	/	*	***
Waterscape	<0.001	0.413	0.436	—	**	/	/	/	/	**
Mountain	0.003	<0.001	<0.001	0.001	—	***	**	***	**	/
Farmland	<0.001	0.431	0.568	0.966	<0.001	—	/	/	/	***
Path	<0.001	0.069	0.138	0.386	0.003	0.271	—	/	/	*
Building	<0.001	0.044	0.118	0.394	<0.001	0.297	0.874	—	/	***
Infrastructure	<0.001	0.021	0.022	0.143	0.010	0.112	0.469	0.262	—	*
Structure	<0.001	<0.001	<0.001	0.004	0.163	<0.001	0.018	<0.001	0.023	—

$p = 0$
*** $p < 0.001$
** $p < 0.01$
* $p < 0.05$
$p > 0.05$

Figure 11. *p* value of post hoc (LSD) pairwise comparisons of the average fixation duration for different landscape elements.

3.4.2. Heatmap Responses to Perceived Restorativeness

Heatmaps can efficiently and directly display the visual attention areas of multiple subjects. After aggregating and overlaying the experimental results from the 81 images, we generated visual attention areas for each type of landscape (Figure 12). Red indicates a key area of visual attention in terms of average fixation duration, yellow and green denote areas with a moderate average fixation duration, and green represents areas with the lowest average fixation duration (the intensity decreases from red to yellow to green) [55].



(a) (b) (c)

Figure 12. Heatmap views. (**a**) Heatmap over the original photograph. (**b**) Semantic segmentation picture. (**c**) Semantic segmentation picture with a heatmap overlay.

Overall, natural landscapes attracted longer average fixation durations, less eye movement, and more focused attention (Figure 13). From the perspective of perceptual fluency, this means that the participants' visual systems continuously processed natural landscape visuals, requiring less cognitive effort to perceive these landscapes. Semi-natural landscapes had similar average fixation durations and eye movements to natural landscapes but were influenced by certain artificial elements. The artificial landscapes had higher numbers of fixations, eye movements of greater distance, and shorter fixation durations for specific landscape elements (bridges, street lights, and pavilions) than the natural landscapes. The numerous areas of fixation indicate that more cognitive effort was required to process the artificial landscapes, and related research has suggested that less cognitive effort is one of the factors contributing to psychological restoration [80].

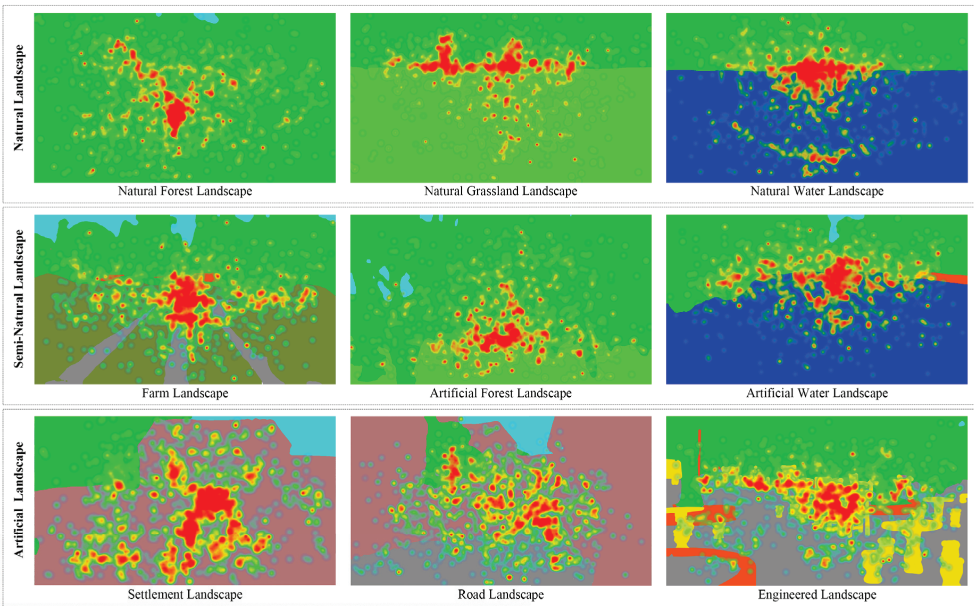


Figure 13. Semantic segmentation heatmaps of different naturalness and landscape types.

Among the natural landscapes, natural forest landscapes generally attracted longer visual fixation durations with a more concentrated area of gaze distribution that was primarily focused on the center of the scene or the paths within the forest, and more attention was paid to distant views and broader vistas. In natural water landscapes, attention was mainly concentrated around the water's edge and the vanishing point of view, spreading to the terrain near the water and reflections of the terrain. This result indicates that in the open water landscapes, the distant and background views more strongly attracted the participants' attention. Natural grassland landscapes have a wide field of view with relatively simple landscape elements in which the participants' visual range was broad and they could focus more easily on the center of the scene and the horizon. However, if there were elements such as trees or pavilions, these became the focus of attention for the participants. Overall, the distribution of gaze points in the natural landscapes was relatively concentrated and uniformly dispersed, with the primary landscape elements of focus being trees, grass, and water.

In terms of the semi-natural landscapes, vegetable plots and distant mountains in the farmland landscape received the most attention from the participants; fixation points were not concentrated on a specific element, as the participants tended to look towards fields and mountains. In the artificial water landscapes, the fixation points were primarily structures along the shore and their reflections, possibly because the complexity of the reflections in the water and the sky was too low to easily attract attention. In the artificial forest landscapes, the fixation points were generally concentrated in the center of the scene, likely because the evenly spaced trees lacked distinctive elements to attract attention.

In the artificial landscapes, when the participants observed settlement landscapes, their attention was concentrated mainly on distinctive landscape elements (couplets, eaves, and decorative paintings) and the intersections of main buildings or landscape elements, spreading to surrounding green landscapes and architectural features. The primary focus for road landscapes was the vanishing point of view, which then spread to architectural structures (doors, windows, and roofs) and green landscapes on both sides of the road. In the engineered landscapes, the fixation points were dispersed, but the main focus was on buildings, roads, and structures.

4. Discussion

4.1. Relationship between Actual Naturalness, Perceived Naturalness, and Restorative Quality

This study revealed a significant correlation between perceived naturalness and perceived restorativeness ($p < 0.001$) that sometimes even surpassed the objective physical properties of the landscape. Objective and subjective data indicated that as the naturalness of the rural landscapes decreased, there was a significant decrease in the participants' alpha values ($p < 0.05$), beta values ($p < 0.05$), and RCS scores ($p < 0.001$), resulting in lower levels of restorativeness, consistent with previous research [82]. Why does a higher level of naturalness promote psychological health? There are several possible explanations. First, humans have an innate tendency to focus on and engage with natural environments, and elements such as bodies of water flora, and fauna can stimulate positive emotions and, thus, have a therapeutic effect [83]. Second, wilder or more natural environments often provide a refuge from the tensions of daily life, helping to alleviate psychological and physiological stress [84]. This phenomenon may be due to the deep connection between humans and nature and the emotional dependence on the natural environment that shapes people's perceptions of it, which in turn affects the perceived restorative value of the natural environment [85]. Although early studies indicated a correlation between perceived naturalness and restorativeness, these studies lacked empirical support [82,86]. This study confirms this relationship with empirical evidence.

The results showed a significant positive correlation ($p < 0.001$) between the perceived naturalness and actual naturalness of rural landscapes, with discrepancies primarily being due to differences in their definitions. Typically, the addition of natural elements to a landscape (such as green spaces and bodies of water) enhances people's perception of its naturalness [87]. In natural environments, the perceived naturalness level is usually slightly lower than the actual naturalness level, whereas in artificial environments, the perceived naturalness level tends to be higher than the actual naturalness level. This phenomenon arises because the complex and varied features of purely natural environments are difficult to fully perceive and evaluate [88], whereas any natural elements in artificial environments exceed expectations and may, thus, be seen as prominent natural features [55]. This contrast effect leads to higher perceived naturalness, even in landscapes with a lower level of actual naturalness [33]. In summary, our findings highlight the complex relationship between perceived and actual naturalness and suggest that when assessing and designing rural landscapes, consideration should be given to the potential discrepancies between people's perceptions of naturalness and the actual natural state to more effectively construct landscapes with restorative potential.

Interestingly, we found that the urban participants gave significantly higher scores for the perceived restorativeness of rural landscapes than the rural participants. This difference may be due to the faster-paced lives and greater stress faced by urban than rural residents. For urban residents, rural landscapes present a sense of novelty that can significantly enhance their psychologically restorative experience. Conversely, rural residents, who live in rural settings daily, have gradually adapted to the tranquil lifestyle of these landscapes and, therefore, may not experience the same restorative effects [22].

4.2. Relationship between Landscape Type and Restorative Quality

Our findings showed significant differences in emotional states among the participants when observing different types of rural landscapes with the same level of naturalness, leading to varied restorative effects. These findings are consistent with previous research [89,90] and further confirm the critical importance of certain spatial qualities and landscape types for restorativeness.

Within the natural landscapes, the impact of natural forest landscapes on psychological restorativeness was most significant, followed by natural water landscapes and natural grassland landscapes. According to SRT, natural environments significantly facilitate recovery from psychological stress [20]. The diverse vegetation layers in forests create a landscape that balances openness and enclosure, enhancing feelings of freedom while maintaining a sense of privacy and mystery. ART posits that effective restorative environments should support unconscious attention restoration [22]. The rich natural elements of natural forests spontaneously engage people's interest and attention, facilitating an involuntary attention shift that alleviates mental fatigue [91]. In contrast, although water landscapes are generally favored [92], natural water landscapes suffer from significant weather and water flow variations, leading to lower environmental stability and consequently weaker restorative potential [93]. Moreover, untended rural natural grassland landscapes are less restorative because they may generate feelings of unfamiliarity and insecurity [94].

In the semi-natural landscapes, artificial forest landscapes had a more significant restorative impact than farm landscapes and artificial water landscapes. Artificial forest landscapes possess restorative properties that are similar to those of natural forests, and due to their greater familiarity, offer a strong sense of ease and shelter, significantly enhancing feelings of comfort and relaxation [95]. However, the restorative effects of artificial forest landscapes in this study were weaker than those of natural forests. This may be due to the dense planting in artificial forests to ensure yield, which results in a more enclosed environment, whose visual monotony and sense of enclosure may impair an individual's stress recovery capability [8,96]. Previous studies have shown a stronger preference for natural water landscapes than highly managed artificial water landscapes [92]. The reasons for this result may be related to rapid development activities that have damaged original water landscapes, altered the flow paths of natural water systems, and deteriorated the water quality of rivers and lakes. Moreover, the extensive use of hard materials in artificial water landscapes and the noisy background in these environments often exacerbate perceived stress [22].

In the artificial landscapes, settlement landscapes were ranked highest for restorativeness, followed by road landscapes, and then engineered landscapes. We offer two possible explanations for the high restorativeness of settlement landscapes among artificial landscapes. First, the cultural (e.g., poem walls, pavilions) and artistic (e.g., floral windows, landscape statues) elements within settlement architecture, which are decorative features with significant aesthetic value, positively affect psychological and physiological recovery [50]. Second, people have a strong preference for landscape archetypal elements that are similar to those in their hometowns, as this fosters place attachment, thereby positively affecting perceptions of restorativeness and psychological recovery [97]. Additionally, although road landscapes and engineered landscapes benefit rural areas to some extent, their restorative potential is relatively weak. This may be due to rapid urbanization impairing the rich cultural, scientific, and aesthetic features of rural areas [98], leading to a loss of local characteristics [99], homogenization, and the imitation of urban features in rural engineered landscapes [100].

4.3. Relationship between Landscape Elements and Restorative Quality

In this study, trees proved to be the most restorative elements in rural landscapes, followed by waterscapes and farmland. Trees not only reduce air pollution and enhance carbon sequestration but also decrease levels of anxiety, depression, anger, and fatigue through contact with them, thereby promoting public health and producing environmental benefits [89]. Waterscapes are another element with great restorative potential; in this study, we found that waterscapes provided significantly greater restorativeness than farmland ($p < 0.001$). This phenomenon may be due to the varied ecological functions of waterscapes, which not only support critical activities such as agricultural production and irrigation but also provide people with abundant natural resources and space [101]. Additionally, waterscapes form typical rural landscapes such as streams, ponds, and channels, which do not serve as places for recreation, social activities, and mental fulfillment [22]. However, unfamiliar water areas also present certain dangers that potentially reduce their restorativeness [73]. Finally, because farmlands preserve the original natural environment while adding productive attributes, they evoke a stronger sense of familiarity than other landscape elements, thus reducing stress and enhancing restorativeness [102].

Our research findings revealed that artificial landscapes such as buildings, roads, structures, and infrastructure have relatively weak restorative potential for mental health, supporting previous studies that have suggested that artificial elements have a lower restorative quality [57]. Additionally, different artificial landscape elements have varying impacts on restorativeness. For example, buildings, as a form of cultural heritage, can to some extent stimulate positivity, thus mitigating the negative effects of hard landscapes generally, and, therefore, possess certain restorative properties [103]. However, roads, structures, and other hard landscape elements (such as ground surfaces, guardrails, retaining walls, and street lamps) typically carry lower restorativeness scores, which may be due to several reasons. First, hard landscapes often lack vegetation cover, which reduces their naturalness and, thus, diminishes their restorativeness [104,105]. Second, hard structures such as roads and infrastructure may enhance the perception of human intervention, reducing the attractiveness of and affinity with the landscape. Poor management and a lack of comfortable experiences can further diminish the restorativeness of these elements [73].

The overall relationship between the landscape element indices and perceived restorativeness indicated that higher proportions of natural landscape elements such as trees and lower proportions of hard landscape elements such as buildings, roads, and structures typically lead to longer average gaze durations, which is beneficial for mental health. However, the same elements may yield different restorative outcomes in different landscapes. In the natural landscapes in this study, an increased proportion of grass led to reduced restorativeness scores, which is consistent with previous studies that found grassland landscapes to be less restorative than natural forest landscapes and water landscapes. This may be due to the uncontrolled growth and lack of maintenance of grasslands in rural areas, which elicits a fear of 'wildness', leading to perceptual barriers and a loss of a sense of security [106,107].

Although natural elements are generally considered to have positive restorative effects, we found that increasing the presence of elements such as mountains and water in semi-natural landscapes actually leads to a decrease in restorativeness. We propose three possible explanations. First, the disharmony between natural elements and man-made structures may indirectly weaken the restorative effect of the natural elements, disrupting the sense of environmental harmony [104]. Second, the insufficient management and maintenance of semi-natural landscapes are also key factors. Increased natural elements may create greater demands for management and maintenance; if these demands are not adequately met, then the overall landscape quality may decline, which can cause disappointment or discomfort, reducing environmental restorativeness [108]. In summary, from the perspective of perceived restorativeness, landscape designers need to cautiously add artificial elements to rural landscapes and improve the maintenance of natural environments to maintain their restorative potential.

4.4. Implications of the Major Findings

In this study, we employed a psychophysiological approach to understand the impacts of different rural landscapes on human mental health from both the macro (landscape types) and micro (landscape elements) perspectives, based on varying degrees of naturalness. First, the results revealed significant differences between perceived and actual naturalness in the natural landscapes, which may affect the psychological restoration benefits people derive from these environments. Thus, rural managers, environmental scientists, and landscape designers should prioritize the natural elements of rural landscapes and their vast restorative potential. When designing rural landscapes, it is essential to effectively protect and utilize the natural elements within these environments. This includes maintaining and restoring natural vegetation and ensuring water quality. By enhancing the connection between humans and nature, we can maximize the restorative potential of natural landscapes, thereby improving the physical and mental health and overall quality of life for residents. Second, this study demonstrated that different types of rural landscapes provide varying benefits in terms of restoring mental health, even at the same level of naturalness. Therefore, simply considering the degree of naturalness is insufficient. Landscape designers must thoughtfully plan the spatial structure of rural landscapes, selecting or combining various types of landscapes such as farmland, woodlands, water bodies, and settlements according to specific needs. This approach allows for the effective integration of natural resources while simultaneously meeting multiple demands related to ecology, production, and living. Our research affirms the positive impact of certain landscape elements within rural landscapes in promoting health. In organizing modern rural landscape spaces, it is essential to preserve the original texture of the natural landscape and prevent chaos through new buildings and landscaping. Finally, while certain landscape elements may enhance physical and mental health, the restorativeness of a single landscape element cannot fully represent the restorativeness of the entire space, and also varies across different types of landscapes. Therefore, we suggest that the selection and arrangement of landscape elements in constructed rural landscapes are crucial for maximizing a landscape's restorative effects. Incorporating various types of design elements, such as forest paths and waterfront walkways, would create a richer environment. At the same time, uncovering and protecting the local landscape's cultural features also has significant restorative potential. Respecting and integrating local historical and cultural elements, such as couplets, window patterns, and stone carvings, prevents the loss of cultural content in rural landscapes to the blind pursuit of modernization.

4.5. Limitations and Research Opportunities

Although this study uncovers important results, it also has limitations that provide new opportunities for future in-depth research. First, the geographical scope of this study is confined to the rural areas of Guangzhou, which may limit the wider applicability of the results. Given the distinct regional characteristics of rural landscapes, the Guangzhou rural areas selected for this study, with their relatively high level of development and unique cultural environment, can be considered a typical sample of modernized rural China. However, future research should consider expanding the scope to diverse geographical areas with different natural conditions and cultural backgrounds to more comprehensively assess the applicability of our findings. Second, the sample size selected for this study was relatively small and focused only on the young population, without considering differences in restoration preferences among other age groups. Although the experiment assessed restorativeness along both physiological and psychological dimensions using four measures and conducted a detailed analysis of the participants' characteristics to minimize problems resulting from the limited sample, future studies should aim to increase both the size and the diversity of the sample to improve the scientific rigor and precision of the results. Finally, the processed images used in this study may not have fully reflected the participants' perceptions of the landscapes accurately. Although studies show that photographs can simulate the restorative effects of real environments to some extent, multisensory experiences in the actual environment (such as visual, auditory, and olfactory experiences) are also crucial for assessing restorative potential. Therefore, future research should consider conducting field measurements to obtain more accurate data on landscape perceptions.

5. Conclusions

Rural landscapes, which are distinguished by their unique ecological properties and notable therapeutic potential, are widely regarded as ideal environments for psychological restoration. This study found that perceived naturalness, rather than actual naturalness, is a key determinant of perceived restorativeness, with higher levels of perceived naturalness significantly enhancing the restorative benefits of a landscape. Different landscape types and elements were found to provide different levels of restorative benefits for mental health. Forests and waterscapes within natural settings demonstrated exceptionally high restorative potential. In semi-natural landscapes, the perceived restorativeness of artificial forests significantly exceeded that of farmland and artificial water landscapes while within the artificial landscapes, settlements exhibited notable psychologically restorative effects. The restorativeness of rural landscapes significantly increased with the addition of natural elements such as trees and water bodies. Conversely, it diminished when the proportion of hardscape elements, such as roads and structures, increased. Additionally, we found that the perceived restorativeness of identical elements can vary across different settings. Consequently, we suggest that the restorative impact of rural landscapes could be enhanced by optimizing landscape element configuration, appropriately protecting and managing the landscape, enriching cultural values, and minimizing artificialness. The quantitative and qualitative findings of this study complement each other, providing scientifically robust empirical support for the restorative effects of rural landscapes. The findings will help maximize the health potential of modern rural environments, thereby enhancing human psychological health and well-being.

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Data Availability Statement: The data that support the findings of this study are available from H.S. and X.H. upon request.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

This study selected the Restorative Components Scale (RCS) and Perceived Restorativeness and Naturalness Scale (PRNS) as the basis for evaluating perceived restorativeness on the psychological level. When filling out the scales, participants were asked to imagine themselves in the scenes presented in the images and rate them based on their agreement with the descriptions. Lower values indicate more negative evaluations, while higher values indicate more positive evaluations.

Table A1. Restorative Components Scale (RCS).

ART Components	Items	Scoring
Being away	1. I am in a different setting than usual 2. I do something different than I usually do 3. I am in a different environment than usual 4. When I am here I feel free from work and routine 5. When I am here I feel free from other people's demands and expectations 6. When I am here I do not need to think of my responsibility 7. I am away from my obligations	1 2 3 4 5 1 2 3 4 5 1 2 3 4 5 1 2 3 4 5 1 2 3 4 5 1 2 3 4 5 1 2 3 4 5
Extension	8. The elements here go together 9. The surroundings are coherent 10. All the elements constitute a larger whole 11. The existing elements belong here	1 2 3 4 5 1 2 3 4 5 1 2 3 4 5 1 2 3 4 5
Fascination	12. There is plenty to discover here 13. There are many things here that I find beautiful 14. There is plenty that I want to linger on here 15. This setting has many things that I wonder about 16. There are many objects here that attract my attention 17. I am absorbed in these surroundings	1 2 3 4 5 1 2 3 4 5 1 2 3 4 5 1 2 3 4 5 1 2 3 4 5 1 2 3 4 5
Compatibility	18. The environment gives me the opportunity to do activities that I like 19. I can handle the kinds of problems that arise here 20. I rapidly adapt to this setting 21. There is an accordance between what I like to do and these surroundings 22. I am capable of meeting the challenge of this setting	1 2 3 4 5 1 2 3 4 5 1 2 3 4 5 1 2 3 4 5 1 2 3 4 5

Table A2. Perceived Restorativeness and Naturalness Scale (PRNS).

Experimental Images	Items	Scoring
 (Examples of the experimental images, 81 in total)	Restoration Naturalness	1 2 3 4 5 6 7 1 2 3 4 5 6 7

Appendix B

All of the statistical analyses were conducted using IBM SPSS Statistics 27 and Microsoft Excel 2021. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Table A3. Tests of within-subject effects on RCS responses among three degrees of naturalness.

Measures	Type III Sum of Squares	df	Mean Square	F	*p*	Partial Eta Squared
Type Error	36.901 34.128	1.671 165.429	22.083 0.206	107.046	<0.001	0.520

Table A4. Tests of within-subject effects on three degrees of naturalness of RCS responses among different landscape types.

Naturalness	Measures	Type III Sum of Squares	df	Mean Square	F	*p*	Partial Eta Squared
Natural landscapes	Type Error	7.694 32.935	1.872 185.340	4.110 0.178	23.127	<0.001	0.189
Semi-natural landscapes	Type Error	8.479 39.646	2.000 198.000	4.239 0.200	21.172	<0.001	0.176
Artificial landscapes	Type Error	24.527 48.464	2.000 198.000	12.263 0.245	50.102	<0.001	0.336

Table A5. Tests of within-subject effects on four frequencies of brain waves (α1, α2, β1, and β2) among three degrees of naturalness.

Waves	Measures	Type III Sum of Squares	df	Mean Square	F	p	Partial Eta Squared
α1	Type Error	0.652 5.372	1.662 64.813	0.393 0.083	4.737	0.017	0.108
α2	Type Error	0.773 5.901	2 78	0.386 0.076	5.107	0.008	0.116
β1	Type Error	0.820 5.340	1.736 67.709	0.473 0.079	5.991	0.006	0.133
β2	Type Error	0.509 4.576	1.642 64.030	0.310 0.071	4.338	0.023	0.100

Table A6. Tests of within-subject effects on average fixation duration responses of eye-tracking among landscape elements.

Measures	Type III Sum of Squares	df	Mean Square	F	p	Partial Eta Squared
Type Error	0.860 2.408	6.034 235.330	0.142 0.010	13.924	<0.001	0.263

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Article

Geohazard Prevention Framework: Introducing a Cumulative Index in the Context of Management and Protection of Cultural and Natural Heritage Areas

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Abstract: Geohazards pose an essential role to the preservation of cultural and natural heritage areas, given their valuable significance in terms of scenic, natural, and cultural characteristics, forming unique landscapes that require proactive action to achieve sustainable environmental management. To address these challenges, a methodological framework focusing on geohazard prevention, emphasizing the importance of a pre-management stage that enables stakeholders to prioritize resources and implement landscape planning strategies, is proposed in this paper. In this framework, an integrated set of geospatial, geological, meteorological, and other relevant environmental factors to quantify cumulative geohazard zones in heritage areas is utilized. Implementing advanced tools such as geographic information systems (GISs), remote sensing techniques, and geospatial data analysis, a clustering and characterization of various geohazards is obtained, providing a comprehensive understanding of their cumulative impacts. The introduction of a cumulative geohazard index is proposed in this paper to better understand and then assess the impacts of environmental-driven geohazards that may affect cultural and natural heritage areas to be embedded into the impact assessment process. The validation of the proposed geohazard framework and index is performed in the Parrhasian Heritage Park in Peloponnese, Greece. The outcomes of the analysis highlight the need to mitigate geohazard impacts through early and in situ targeted actions to facilitate the decision-making process and contribute to the protection of evolving landscapes with cultural and natural elements for future generations.

Keywords: geohazards assessment; protected areas management; heritage landscapes; visual resources protection; geohazard factor analysis

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1. Introduction

This study focuses on the prevention of geological hazards that affect areas of cultural and natural heritage forming landscapes. In these areas, the objectivity of the esthetic natural and historic, archeological, and cultural characteristics describes their heritage. The combination of valuable natural and human-made features contributes to their significance and visual appeal [1]. These areas are rich in natural resources, possess exceptional beauty, are home to diverse cultures, and have a long history and traditions. It is crucial to recognize these areas as landscapes, and as landscape is a vital aspect of the environment that plays a pivotal role in spatial planning and environmentally sustainable management [2,3]. Furthermore, it is essential to recognize that these "living" landscapes are not merely objective entities but are also perceived subjectively by their users. This is particularly relevant in the context of local communities, which maintain their traditions and live within these landscapes [4,5].

Cultural and natural heritage areas comprising outstanding scenic and cultural assets form exceptional landscapes. These landscapes require protection in order to preserve their scenic, natural, and cultural treasures for future generations in a sustainable manner.

A shared understanding of vision, values, and strategies could guarantee the protection of the environment and motivate a community to work towards the preservation of the heritage identity [5]. The study of the geological evolution of such landscapes is crucial for the conservation of their cultural and natural characteristics. This process occurs over time and is influenced by various environmental factors, including the effects of climate change. In order to ensure the proper management of this evolution, it is necessary to conduct an objective evaluation.

This research concentrates on landscapes of cultural and natural heritage in terrestrial areas with mountainous characteristics due to the multitude of geological processes and environmental factors present in different regions. These processes have contributed to the formation of heritage features and continue to shape them. The valuable characteristics of heritage landscapes demonstrate that nature has generously provided its gifts in the past, which humans have used to inspire, envision, and create their myths, cultures, and lives with respect. Geology and the natural environment have been instrumental in informing people of the most suitable locations to live in for millennia. The materials used to develop their constructions, including temples and other cultural monuments, are also products of this knowledge [6]. These cultural characteristics survive to the present day. Geological history has been identified as a significant factor in the formation of these features [6]. The cultural life of the site is inextricably linked to the character and type of its natural environment. It is the physical space, with its inherent variables and unique formation, that attracts, guides, inspires, and becomes decisive in the production of the cultural trace by people. The relationship between nature and cultural heritage is direct and unambiguous. The Oracle of Delphi would not exist in its current form were it not for the specific geological characteristics of the region. The Parthenon would not have been constructed on the Acropolis if the Holy Rock had not existed. The monument and nature are in harmony with the golden ratio, as evidenced by the proportions of the Parthenon [7,8].

From the geocentric perspective, the geological processes both create and threaten this heritage, which was created years ago. These processes can affect cultural and natural heritage landscapes. While they are mainly endogenous earth processes, they interact with water, temperature, frost, or other environmental factors and occur as geological hazards, or geohazards. Landslides, subsidence, liquefaction, rockfalls, and erosion have profound effects on the cultural and natural characteristics of a site and alter landscapes [7–9]. In the context of sustainable management aimed at preserving cultural continuity and protecting natural beauty, it is essential to systematically observe the geological architecture and history of the area in order to prevent, reduce, and deter geohazards. It is of the utmost importance that cultural and natural heritage sites receive appropriate action during the pre-management stage in order to preserve their sensitive and significant features for future generations [10].

A review of the international literature on the assessment of geological hazards reveals a multitude of similar research projects [10–12]. These studies tend to focus on the assessment of a specific geological hazard, such as landslides or earthquakes, which are known to cause disasters [13–16]. However, the present research adopts a cumulative approach to assessing all geohazards that threaten cultural and natural heritage sites.

The present study addresses the prevention of geohazards that may alter cultural and natural heritage landscapes in order to avoid natural disasters. The main difference between geohazards and disasters is their respective focus and timing. Geohazard prevention entails the implementation of proactive measures designed to identify, assess, mitigate, and avoid potential geohazards before they occur or escalate into disasters. This encompasses a range of actions, including the implementation of assessments, the establishment of monitoring systems, the adoption of land-use planning strategies, and the use of structural or non-structural mitigation measures with the objective of reducing the likelihood or severity of geohazards.

This research focuses on assessment and, in particular, on a cumulative assessment approach for the prevention of all geohazards in an area due to the sensitivity of threatened heritage features. The fundamental principle of the cumulative approach is to assess the impact of all geohazards that are additive or interactive. The additive and interactive effects of geohazards can be repeated over time and distributed over space, and thus they should be "calculated" as a result of changes caused by past, present, and reasonably foreseeable future actions. It is necessary to address a cumulative geological perspective [11,17].

In this paper, a geospatial, integrated geohazard-driven methodological framework for prevention emphasizing the importance of a pre-management stage that enables stakeholders to prioritize resources and implement landscape planning strategies is proposed. This framework introduces a cumulative index to assess the potential impacts on cultural and natural heritage landscapes of terrestrial land. It consists of six functions that are linked in a loop to show the process of continuous improvement and is based on GIS technology. The framework employs a range of tools, methods, and techniques to identify geohazard zones of graded importance and specific locations within them with spatial indications for the prevention and preservation of cultural and natural heritage landscapes. The framework is implemented in the mountainous area of the Parrhasian Heritage Park (PHP), situated on the western side of the central Peloponnese in Greece. The park's landscape comprises a combination of significant cultural and valuable scenic features.

2. The Geohazard-Driven Framework and the Cumulative Index

2.1. Geohazards and Environmental Factors

The proposed geohazard-driven framework and the cumulative index have the potential to contribute to the prevention of evolving landscapes through the implementation of early actions of sustainable management and, should the necessity arise, in situ studies. In order to achieve this, it is essential to understand and assess the impacts of the cumulative geohazards through advanced methodologies and data analysis, as proposed in this study. By addressing these threats, work is contributed to the preservation of these invaluable landscapes and their associated heritage treasures for future generations.

This study first identifies the geohazards (GHs) that pose the greatest threat to the sensitive cultural and natural heritage landscapes under consideration. It then describes for each physical variable (geological characteristics, relief, soil, climate, water, and flora) the environmental factors (F_j) that contribute to the occurrence of each geohazard as follows:

(a) Landslides (GH_1), defined as the downslope movement of rock, soil, and debris, can rapidly and destructively alter terrain, posing a significant threat to human infrastructure and the preservation of unique landscapes of cultural and natural heritage.

(b) Earthquakes (GH_2) caused by tectonic activity have the potential to cause severe ground shaking, surface ruptures, and ground displacements that threaten the structural integrity of cultural monuments and buildings, resulting in irreversible damage and loss of historical artifacts.

(c) Gradual process of weathering (GH_3), influenced by atmospheric conditions, affects the physical and chemical properties of rocks and materials over time, contributing to the deterioration of cultural structures, sculptures, and architectural elements in heritage areas.

(d) Erosion (GH_4), whether caused by water or other environmental factors, represents a persistent threat to the integrity of landscapes, potentially degrading archeological sites, cultural features, and valuable geological formations.

(e) Subsidence (GH_5), which is the gradual lowering or settling of the earth's surface, whether due to natural processes or human activity, can lead to structural instability affecting buildings, monuments, and landscapes in cultural and natural heritage areas. This poses a long-term threat to the preservation of historic sites and contributes to the alteration of topographical features (Figure 1).

GEOHAZARDS (GH_i)	ENVIRONMENTAL FACTORS (F_j)					
	Geology	**Relief**	**Soil**	**Climate**	**Water**	**Flora**
Landslide	Tectonic Structures (Faults, Folds)	Slope	Lithology (Soil types)	Rainfall		
	Lithology (Geological formations)	Aspect			Hydrographic Network	Vegetation Density
	PGA (Peak Ground Acceleration)	Curvature (Slope)				
		Road Network				
Earthquake	Volcanic Activity					
	Tectonic Structures (Faults, Folds)					
	PGA (Peak Ground Acceleration)					
Weathering	Lithology (Geological formations)		Lithology (Soil types)	Land Surface Temperature		Vegetation Density
				Rainfall		
Erosion	Lithology (Geological	Slope	Lithology (Soil types)	Rainfall	Hydrographic Network	Vegetation Density
Subsidence	Lithology (Geological formations)	Topographical Wetness	Lithology (Soil types)		Groundwater	
	Tectonic Structures (Faults, Folds)	Aspect	Land Uses		Hydrographic Network	Vegetation Density
		Elevation				
		Curvature				
		Slope				
		Road Network				

Figure 1. Geohazards and environmental factors grouped per physical environmental variable.

Landslides are influenced by a combination of environmental factors that contribute to the destabilization of slopes. These factors include tectonic structures, lithology, peak ground acceleration (PGA), slope steepness, aspect, slope curvature, rainfall patterns, proximity to rivers, vegetation density, and the presence of roads [12]. These factors play a pivotal role in determining the susceptibility of an area to landslides. The geological stability of an area is influenced by tectonic structures and lithology, while the physical conditions conducive to landslide occurrence are shaped by slope characteristics and environmental cover [13–15,18–24].

Earthquakes, which are primarily driven by tectonic activity, are influenced by several environmental factors such as the presence of volcanic activity, tectonic structures, and peak ground acceleration (PGA) that are key indicators of the seismic hazard of a region [16,25–27]. The geological setting, including active fault lines and the historical occurrence of earthquakes, plays a pivotal role in the assessment of seismic vulnerability.

The process of weathering, which is the gradual breakdown of rocks due to various environmental processes, is influenced by a number of specific factors such as lithology, Land Surface Temperature, and vegetation density [28–30]. The composition of the rock (lithology) affects the susceptibility to weathering, while temperature and vegetation cover influence the rate at which these weathering processes occur.

Erosion, the process of wearing away the earth's surface, is mainly influenced by lithology, slope, rainfall intensity, proximity to rivers, and vegetation density. The type of rock (lithology) influences the resistance of an area to erosion, while slope, rainfall patterns, rivers, and vegetation cover contribute to the susceptibility of an area to erosion [16,24–34].

Subsidence, the sinking or settling of the earth's surface, is influenced by the geological composition (lithology) that plays a role in subsidence potential, while factors such as land use and groundwater conditions can exacerbate the settling of the earth's surface. It is therefore essential to understand these factors in order to assess and manage subsidence risks in a given area [35–38].

2.2. The Framework

The proposed methodological framework is based on a newly introduced index, the Geohazards Prevention Index (GPI), which is used to calculate the geohazard assessment. Additionally, a novel hypothesis is presented that distinguishes this index from current efforts to assess geohazards. To identify potentially hazardous situations, it is necessary to assess all geohazards simultaneously, spatially, and cumulatively [39].

The framework follows an iterative process comprised of six distinct functions. Each function performs internal processes and transmits the results to the next. Each iteration is concluded with the final function, which feeds new data to the next one. The interrelationships between the functions are illustrated in Figure 2.

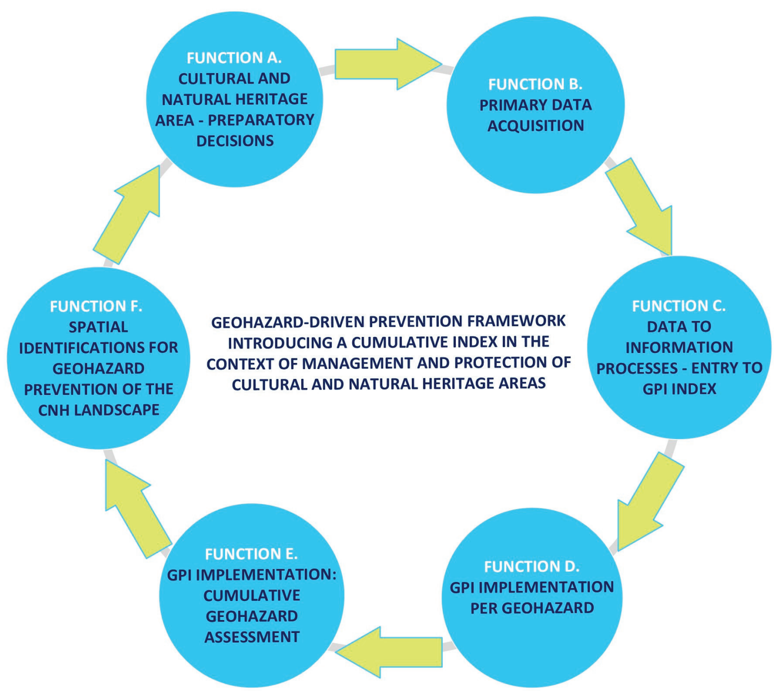


Figure 2. The methodological framework.

The initial function of the methodological framework is Function A. This is responsible for the pivotal decisions that determine the success of the geohazard assessment. Function B is informed by the outcomes of Function A. The necessary data for each identified geohazard and its corresponding environmental factors are collected. The objective is to obtain digital open-data that are available, either from the state and its archival records, from the site management units, or from the utilization of advances in technology. Remote sensing data are particularly useful for rapidly applying the GPI and obtaining prompt results. The same applies to recording cultural and natural heritage features.

Function C is responsible for the conversion of primary collected data into information, with the objective of activating the GPI. In this phase, the requisite digital layers of information are prepared for input into a geographic information system (GIS) platform.

Subsequently, the framework proceeds to Function D, during which the GPI is applied to each geohazard as defined in Section 2.1. The contribution (participation weights, w_j) of each environmental factor, F, is calculated, and geohazard maps are generated for each geohazard, GH, according to the zoning criteria.

All of the elements necessary to implement the GPI for calculating the cumulative geohazard are now available in Function E. The index will be used to calculate the cumulative geohazard. The participation weights for each geohazard in the GPI will be recalculated, and the index will be applied in total. Subsequently, a map of cumulative geohazard zones of graded importance will be generated. The map will then be subjected to a reliability check.

In Function F, a final map identifies the locations of heritage features within each graded geohazard zone. The aim is to indicate those features requiring early prevention and intervention through specific actions and field studies.

The frequency of application of the methodological framework is determined by the body responsible for managing the cultural and natural heritage area. In addition, it is essentially determined by the variation in data relating to the environmental factors that affect geohazards. After an extreme event, such as a strong rainfall event, the framework and the cumulative GPI should be recalculated.

2.2.1. Function A

The implementation of the framework commences with the activation of Function A (Figure 3), where preparatory key decisions will be made pertaining to the cultural and natural heritage area. This is a pivotal phase, as the decisions made at this point will determine the quality of the final outcome. The decisions in question concern, on the one hand, spatial definitions and, on the other hand, the definition of the content of the required information.

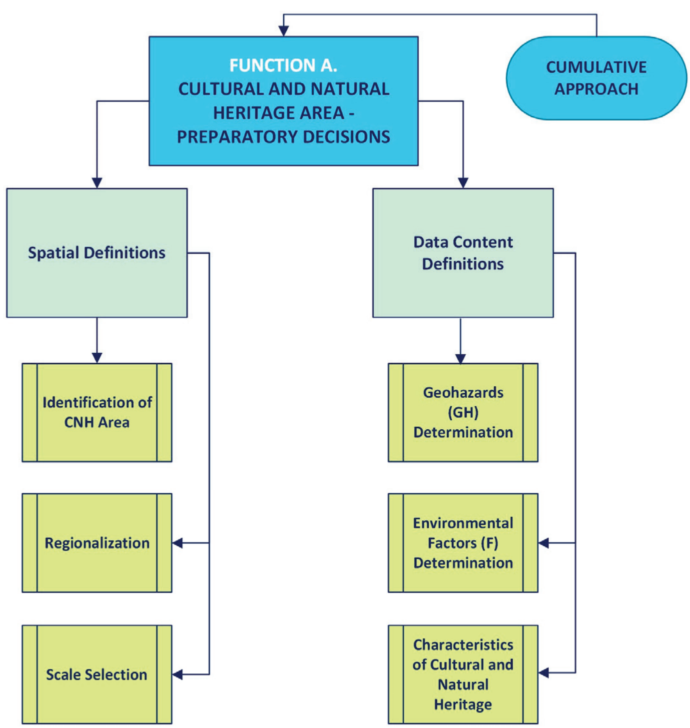


Figure 3. Cultural and natural heritage area—preparatory decisions.

Subsequently, as space is continuous and the boundaries are artificial lines, zones are defined that include adjacent areas of the boundary. This is carried out in order to ensure that critical variables that extend beyond the artificial boundaries, such as flora or fauna habitats, are studied. The area of interest is then regionalized into geographically homogeneous areas. Finally, the scale at which the primary data will be collected, attributed, and presented is determined.

As this is a cumulative approach, determining the content of the required information is of the utmost importance to ensure continuity and, above all, accuracy. For this reason, only the geohazards to be included in the cumulative index model (referred to as GH in the GPI) are identified. For each geohazard, the environmental factors contributing to its occurrence (F in the index) are identified [40]. Finally, it is important to accurately identify the cultural and natural heritage characteristics of the area in the content definition.

2.2.2. Function B

The initial data collection phase, designated as Function B, represents the fundamental stage of the geohazard assessment process (Figure 4). This stage entails the collection and compilation of primary data derived from multitude sources, including digital databases, remote sensing imagery, and archival records. The scope of data acquisition encompasses a comprehensive array of environmental factors essential for evaluating geohazard susceptibility and risk.

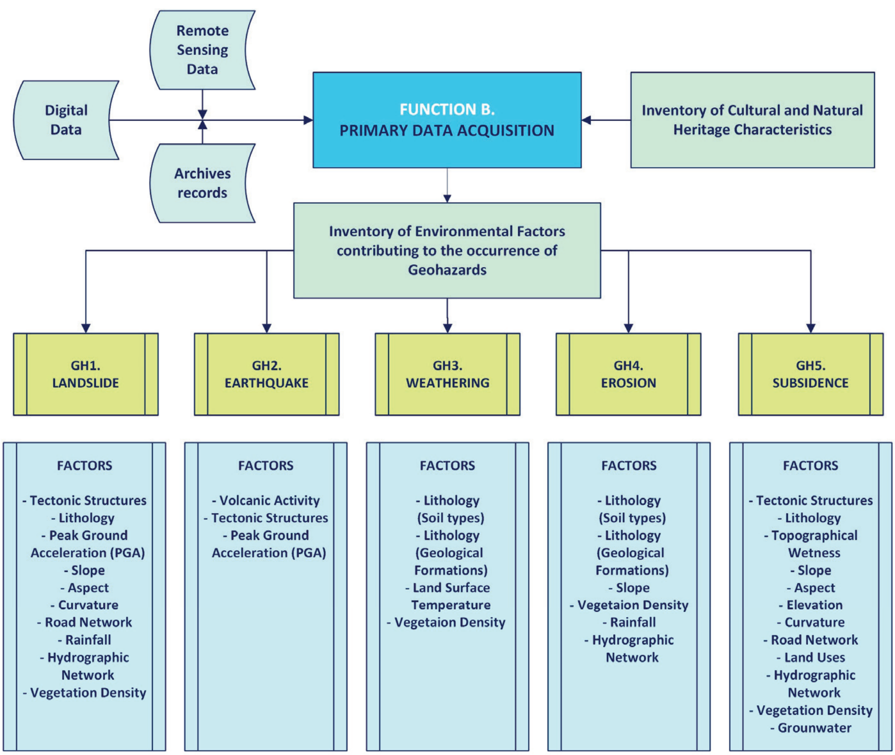


Figure 4. Primary data acquisition.

The principal datasets encompass data pertaining to geological attributes, including fault distributions, lithological compositions, and peak ground acceleration (PGA) values. These datasets provide insights into the underlying geological framework and seismic hazards within the area of interest.

Topographic features, including slope, aspect, curvature, elevation, and the Topographic Wetness Index (TWI), are surveyed in great detail in order to characterize the terrain morphology and assess the terrain stability. This is crucial for comprehending the potential for landslides, erosion, and subsidence. The road network dataset enables the identification of transportation infrastructure vulnerability, while land use data offer understandings into subsidence occurrence. Climate-related variables, including rainfall patterns and Land Surface Temperature (LST), are also critical indicators of weathering. Hydrological features, including river networks and groundwater resources, are evaluated to ascertain the influence of water dynamics on the susceptibility of geohazards. The Normalized Difference Vegetation Index (NDVI), which is employed to quantify vegetation density, offers insights into the health and stability of ecosystems. This information is useful in the assessment of landslides and other geohazards (e.g., erosion and subsidence).

2.2.3. Function C

The function designated as C represents the pivotal stage in the transformation of raw data into actionable information, thereby establishing the gateway to the GPI. Following the selection of pertinent factors, a systematic classification process ensues, categorizing these factors into distinct classes and rank values (Figure 5).

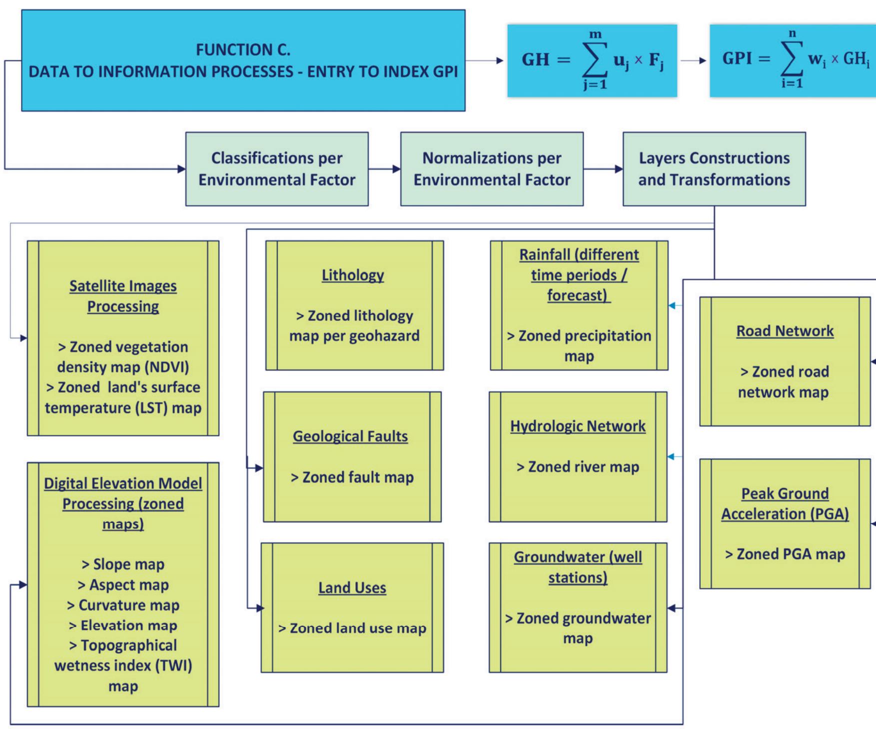


Figure 5. Data for information processes—entry for GPI.

In order to facilitate meaningful comparisons and analyses, each class is assigned a crafted set of standardized ratings. This standardization is achieved through the application of robust statistical methods, including the calculation of the z-score expressed by Formula (1).

$$z - score = \frac{x - xmin}{xmax - xmin} \quad (1)$$

The application of these methodologies ensures that the inherent variability within each factor is normalized, thereby providing a consistent and equitable basis for assessing geohazard potential across different parameters. This harmonization process establishes the foundation for subsequent aggregation of factors within the GPI, thereby providing a comprehensive framework for evaluating cumulative geohazard risk within the CNH area.

In addition, the use of geographic information system (GIS) software (QGIS Desktop version 3.28.11) enabled the generation of distinct layers for each factor, thereby enhancing the analytical capabilities of the study. The utilization of Landsat 8 satellite imagery enabled the generation of zoned map layers for vegetation density (NDVI) and Land Surface Temperature. These layers offered understandings into the dynamics of flora and thermal variations across the area of interest.

The utilization of digital elevation models (DEM) enabled the creation of additional zoned map layers, which delineated the terrain characteristics. These encompassed zoned maps for slope, aspect, curvature, elevation, and the Topographic Wetness Index, providing detailed representations of the topographic features that are crucial for the assessment of terrain stability and vulnerability to geohazard events.

Moreover, zoned map layers were developed for lithology, faults, land uses, peak ground acceleration, rainfall distribution, rivers, groundwater, and road networks. Each of these layers provides essential spatial data pertinent to geohazard assessment. These layers serve as foundational datasets for subsequent analyses, facilitating the integration of diverse environmental factors into the GPI (Formula (2)).

The final cumulative geohazard GPI, which may be caused in the cultural and natural heritage site by n identified geohazards, is the sum of the calculated hazard of each geohazard (GHi), where i = 1 to n, expressed in terms of the total geohazard with the significance of the contribution of each geohazard to it (i.e., multiplied by the corresponding identified weight w_i).

$$GPI = \sum_{i=1}^{n} w_i \times GH_i \tag{2}$$

Consequently, each geohazard (GH) is calculated as the sum of m environmental factors (F_j), where j = 1 to m, multiplied by the corresponding identified weight of the factor (u_j), expressed by Formula (3).

$$GH = \sum_{j=1}^{m} u_j \times F_j \tag{3}$$

2.2.4. Function D

The application of the Analytic Hierarchy Process (AHP) [41] to assign weights to each factor for individual geohazards is the fundamental aspect of Function D (Figure 6). This ensures a systematic and rigorous assessment process.

AHP is a decision-making methodology developed by Saaty in 1980 that is widely used for complex multi-criteria decision analysis problems [41]. The process involves pairwise comparison of criteria or factors based on their relative importance to a decision problem (Figure 5). The steps are as follows: structure the hierarchy; perform pairwise comparisons (use a scale to compare each pair of criteria); calculate weights (derive priority scales from the comparisons); synthesize results (combine the weights to determine the best decision); and check consistency (ensure the comparisons are consistent).

In AHP, decision-makers engage in pairwise comparisons of factors and assign subjective numerical values representing their relative importance. The pairwise comparisons are frequently conducted using a scale from 1 to 9, where each number represents a specific level of relative importance or preference (equal importance (1); weak or slight importance (3); moderate importance (5); strong importance (7); extreme importance (9); and intermediate values (2, 4, 6, 8) that are used to represent compromises between the preferences in the scale). Subsequently, the comparisons can be organized into a Pairwise

Comparison Matrix (PCM), where each element is compared with each other, including itself [41].

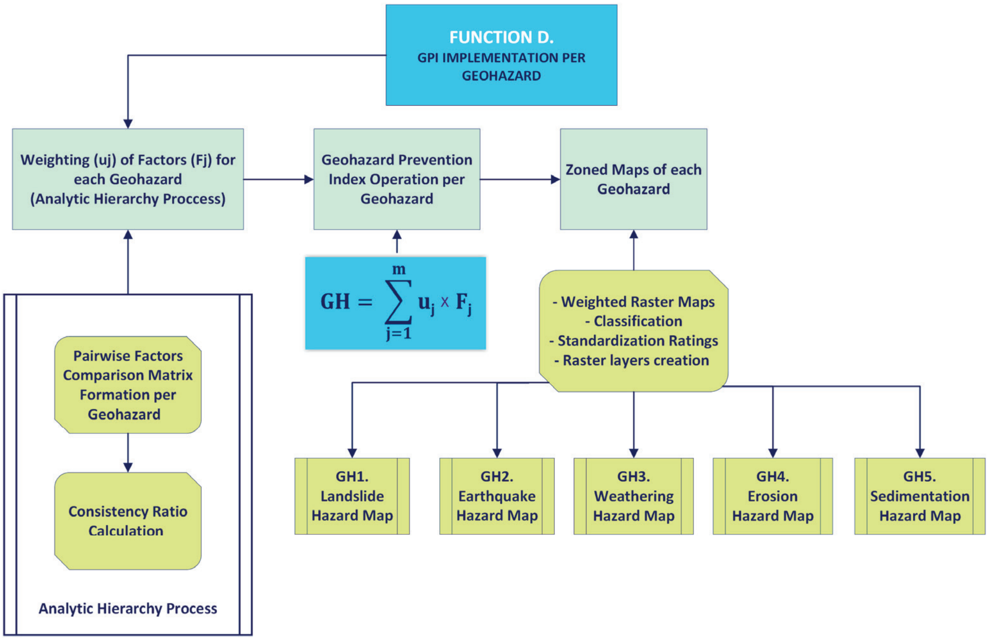


Figure 6. GPI implementation per geohazard (GH).

To ensure consistency and reliability in the pairwise comparisons, consistency ratios (CRs) are calculated for each PCM that serve to quantify the degree of agreement or consistency observed in the pairwise comparisons. Should the consistency ratio exceed a predefined threshold, typically 0.1, adjustments are made to ensure greater coherence in the comparisons [41].

Once the pairwise comparisons have been completed and consistency achieved, the Analytic Hierarchy Process yields weight vectors representing the relative importance of each factor for each geohazard. The steps after constructing the PCM are normalizing the PCM (summarizing each column and dividing each element of the matrix by the sum of its column), averaging the normalized columns, and finally dividing each sum by the number of criteria to obtain the weight vector w. These weight vectors serve as the foundation for aggregating the factors and generating weighted raster maps through the use of geographic information system (GIS) software [42].

The weighted raster maps integrate the influence of each factor on geohazard susceptibility, thereby providing a comprehensive spatial representation of geohazard potential within the area of interest. Subsequently, zoned maps of geohazards are generated by summing the weighted values of each factor and standardizing them for every geohazard. The zoned maps offer insights into the spatial distribution and severity of geohazards, thereby enabling informed decision-making and risk management strategies tailored to the specific characteristics of each hazard type and its underlying contributing factors [43].

2.2.5. Function E

In Function E, the Analytic Hierarchy Process is employed once again, this time to determine the relative importance of the different geohazards within the area of interest (Figure 7). Through pairwise comparisons, weights are assigned to each geohazard based on its perceived significance, ensuring a systematic and informed decision-making process. The reliability and coherence of the pairwise comparisons are rigorously monitored through the use of consistency ratios. Each geohazard is assigned a weight, and geographic information system (GIS) software is employed to aggregate the data, thereby creating a weighted raster map of the GPI. This index serves as a quantitative measure of the cumulative geohazard potential.

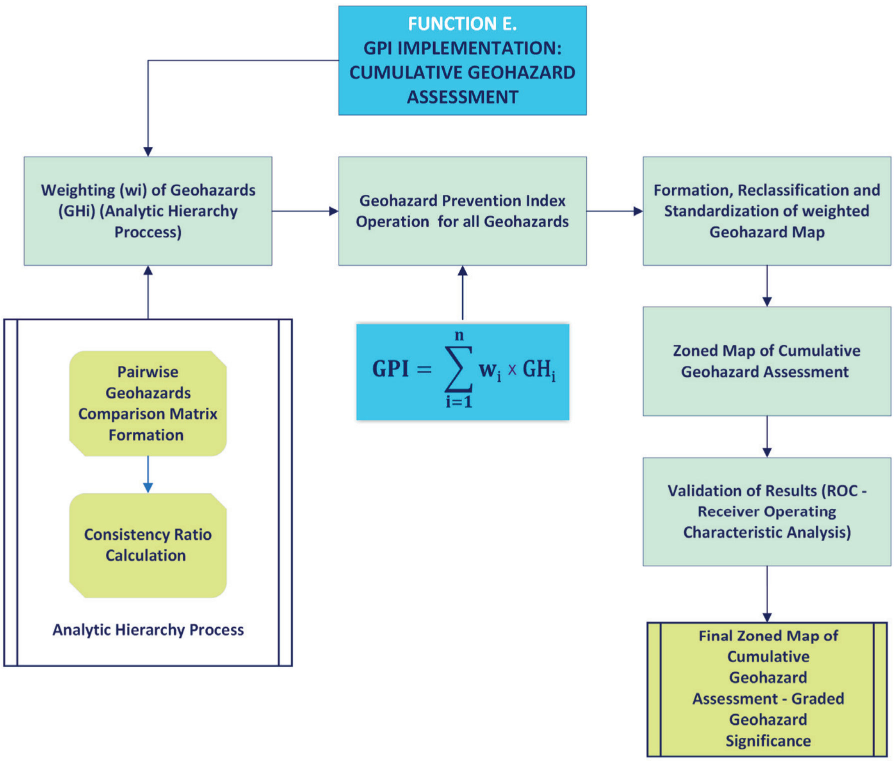


Figure 7. GPI index implementation: cumulative geohazard assessment.

Subsequently, the GPI is standardized, after which a new map is generated. The final map of the cumulative geohazard map is then generated by ranking the standardized GPI values. This process yields insights into the spatial distribution and severity of geohazard risks. To validate the accuracy and reliability of the results, a Receiver Operating Characteristic (ROC) analysis is conducted, comparing the model's predictive performance against observed geohazard occurrences [44]. The validated results are used to produce the final zoned map of the cumulative geohazard assessment, which delineates graded geohazard significance. The map provides understandings that enable targeted mitigation efforts and informed decision-making to mitigate geohazard risks and enhance overall disaster resilience.

2.2.6. Function F

Function F plays a pivotal role in the integration of the methodological framework, as illustrated in Figure 8. It establishes a spatial relationship between the final zoned map of cumulative geohazard assessment, the landscape character zones, and the cultural and natural heritage characteristics of the area of interest. The outcome of these relationships is the identification of sub-zones of notable geohazard significance for the heritage features they contain. The objective is to conserve these heritage features and, consequently, to safeguard the landscape in which they are situated. This may be achieved either by considering the cumulative impact of the geohazards present in the area or by providing detailed information on each hazard separately. The methodological framework assists planners and managers in determining the prevention indications required to mitigate geohazards over time, prevent their further evolution, and enhance the protection of heritage features. These prevention indications may take the form of specialized actions or in situ studies, depending on the significance of the geohazard and the type, detail, and context of the heritage features in question.

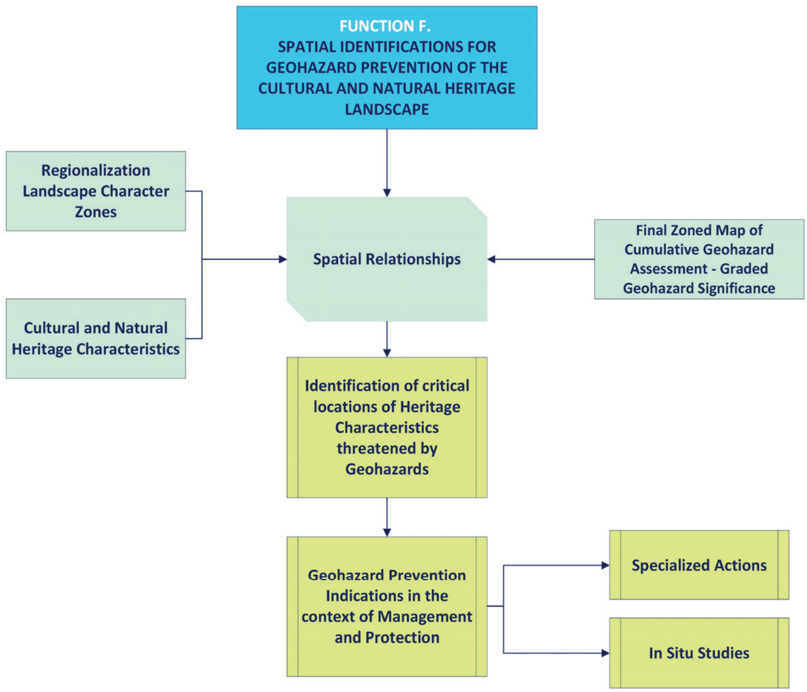


Figure 8. Spatial indications for geohazard prevention.

3. GPI-Based Framework Subject to Field Testing

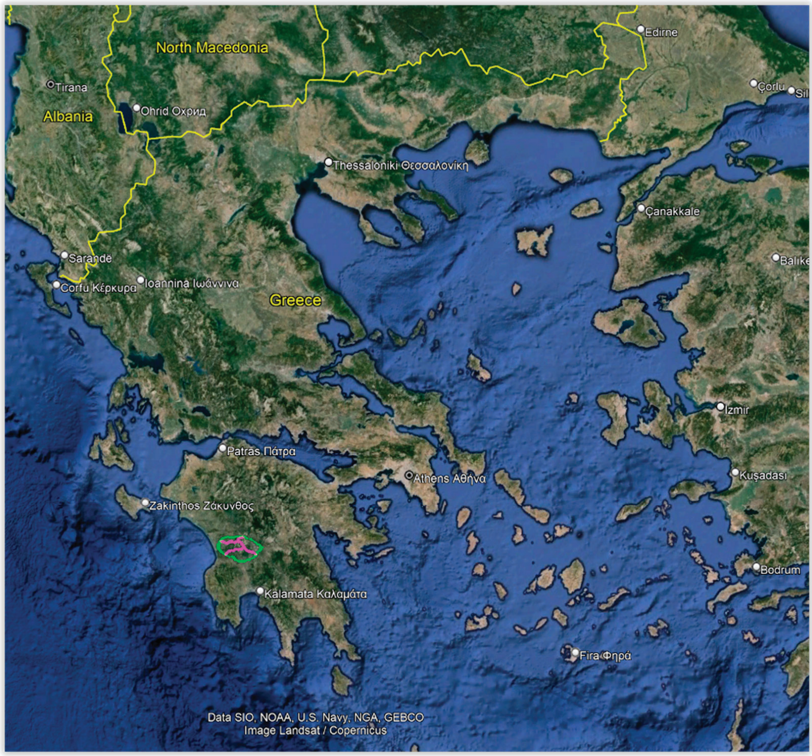
3.1. The Parrhasian Heritage Park, Landscape Character Zones, and Heritage Characteristics

The implementation of the proposed GPI-based framework was carried out in the Parrhasian Heritage Park (PHP), a region situated in Peloponnese, Greece. The area is defined by its delineated boundaries, which encompass four sub-areas that have been identified as landscape character zones. These zones have been derived from a comprehensive regionalization study that has examined the rich cultural and natural heritage of the area in quest [45]. Moreover, the area is subject to geological hazards that affect it and the associated environmental factors to which each geological hazard is related.

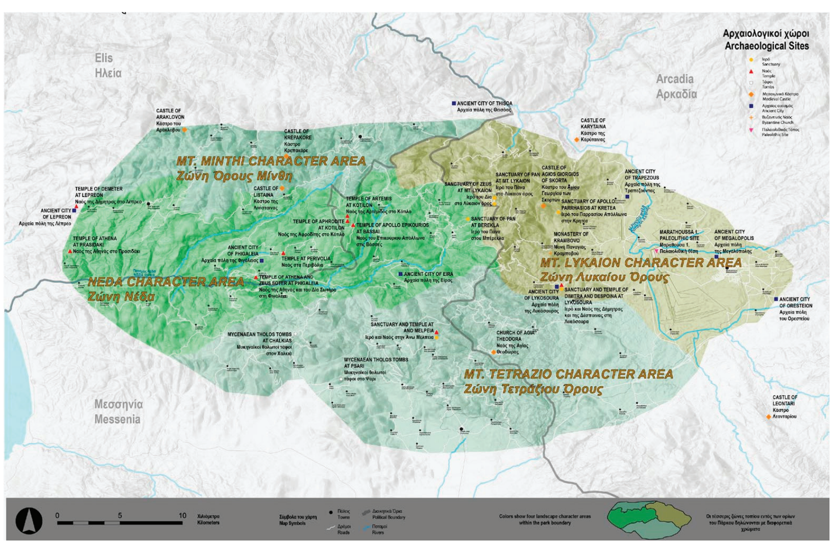
3.1.1. The Parrhasian Heritage Park

The PHP is situated in the western part of Central Peloponnese, encompassing an area of 670 km^2. The designation of PHP is in reference to the ancient name Parrhasia, which was historically regarded as the oldest inhabited area in mainland Greece. The inhabitants of the ancient region (the Parrhassians) are referenced in Homer's Eliad, Rhapsody B. They fought on the side of the king Agamemnon in the Trojan War [46].

At the regional level of self-government, it occupies part of two regions: the Region of Peloponnese and the Region of Western Greece. The PHP comprises portions of three prefectures: Arcadia, Elis, and Messinia. Figure 9a illustrates the location of the PHP within the broader context of the Peloponnese region in Greece. Figure 9b presents a more detailed representation of the PHP [47]. The coloured areas in the picture are the landscape character zones of the PHP. The text of the image is bilingual (English and Greek translation).



(**a**)



(**b**)

Figure 9. (**a**) The PHP in Greece. (**b**) The PHP in detail.

At the municipal level, the PHP consists of five municipalities. In the Peloponnese region, the PHP extends from east to west through the municipalities of Megalopolis (which occupies 37% of the PHP), Oichalia (31%), and Trifylia (7%). In the region of Western Greece, from west to east, it occupies part of the municipalities of Zacharo (14%) and Andritsaina Crestenon (about 10% of the PHP). It is noteworthy that the PHP does not include any Natura 2000 sites, although it does encompass a small portion of a wildlife sanctuary in its south–central region, namely Oichalia.

The area is distinguished by the presence of three major mountain peaks, with Mount Minti to the north, Mount Tetrazion to the south, and Mount Lykaion to the east. Mount Lykaion serves as a natural boundary between the watershed areas to the east and west. The Lykaion is the source of the springs and the surrounding mountains that feed the Neda River. This river flows from east to west through the area and ultimately empties into the Kyparissiakos Gulf [46]. The PHP is dominated by four gateway cities, which are the largest cities in the region, and each has a zone of influence around them. The gateways are located in distinct local zones of the region and are Megalopolis in Arcadia to the east, Andritsaina to the north, Nea Figalia in Elis to the west, and Diavolitsi in Messinia to the south [46].

The PHP is a geologically distinct area in the Peloponnese with significant natural and cultural characteristics that form visual resources. It has been delineated and systematically studied by a scientific team comprising members of three universities: the University of Arizona, the National Technical University of Athens, and the University of Patras, and has been proposed to be established as a protected landscape. This research collaboration has been ongoing since its inception and continues to this day [46].

3.1.2. Landscape Character Zones and Heritage Characteristics

The concept of cultural and natural heritage sites being considered landscapes is a proposition put forth in the literature. Landscapes, with their tangible and intangible dimensions, have particular natural features, prominent or particularly distinctive elements (such as particular geological formations, etc.), despite their biodiversity. These elements are the result of ecological, physical, functional, and anthropogenic relationships that reflect the characteristics of socio-economic systems [48,49]. Furthermore, landscapes have intangible relationships with their inhabitants, or with the inhabitants of wider areas, or with their visitors, which can be historical or collective in nature, symbolic, emotional, and esthetic [50]. In most cases, they form a relative "totality" that links them, united by one or more main characteristics. This unity in diversity gives the place (locus) its distinctive character, which can be described as a 'landscape' [50,51].

The research hub of the three universities identified in the PHP four landscape character zones [47,52–54]. The landscape zones of Mount Lykaion, Mount Tetrazion, Mount Minthi, and Neda comprise the final boundary of the PHP (Figure 10).

- The Minthi landscape zone, located north of the Neda River, was a site of conflict between local Greek barons and invading Frankish crusaders during the Middle Ages. It encompasses the summit of the mountain range and its steep limestone lower slopes.
- The Mount Tetrazion landscape zone is demarcated by the point where the extensive oak-covered slopes of the mountain emerge onto the plain below. It is centered around the limestone peak of Mt. Tetrazion, formerly known as Mt. Nomia, where it was believed that the god Pan had his mountain pastures.
- The landscape character zone of Mt. Lykaion is situated in a seismically active region, which has resulted in the emergence of seven springs and water sources [55,56]. The boundary for the zone is defined by Mount Lykaion and the lower slopes to the north and south of the River Alpheios, which is the longest river in the Peloponnese with a catchment area of 3700 km^2, while to the east it includes Megalopolis and its lignite mine.

- The Neda landscape zone lies at the point where the Neda River rises from the steep mountain valleys in an extraordinary gorge to its edge before the river exits into the plain.

Every August, a series of cultural events is organized by local residents throughout the PHP.

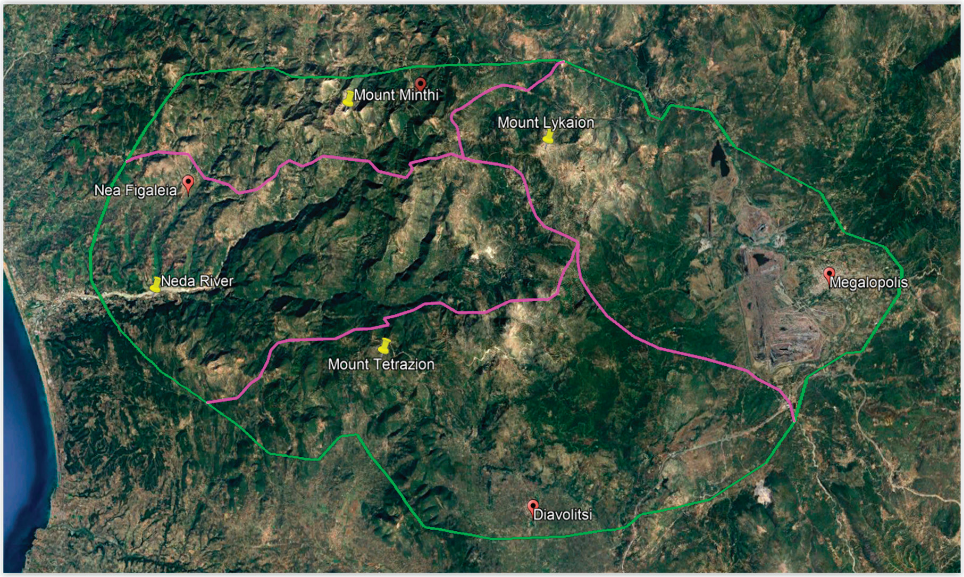


Figure 10. Landscape character zones (purple lines) with three mountain volumes and four gateway cities. Green line represents the PHP's boundary.

The Peloponnese exhibits a high degree of geological, geomorphological, and climatic variability, as evidenced by the region's diverse range of regional and local activities over time. The bedrock and typical landforms are primarily composed of Mesozoic limestone, which is the result of tectonic activity and major events such as floods, earthquakes, and river sediment deposition [55,57,58]. The result of these activities is a diverse landscape comprising a multitude of features within a relatively confined geographical area. These include mountains, limestone caves, gorges, rocky outcrops, forests, rivers, waterfalls, valleys, springs, ancient cities, sanctuaries, and picturesque villages that illustrate a rich cultural and natural history [56].

The mountains in the area were formed in an ancient ocean that existed before the Mediterranean, between 175 and 50 million years ago. The uplift of the seabed to its current height required deep faulting, which resulted in the stacking of 1000-meter-thick layers on top of each other. The erosion caused by rivers and streams in this region has been significantly influenced by fault patterns. Variations in soil types and agricultural fertility are likely to follow underlying geological patterns. Springs emerge from the fault zones, acting as natural plumbing systems to carry water through the fractured and sheared rock. Mountain villages were typically established at spring sites. In contrast to previous mountain buildings, the Peloponnese is currently undergoing a process of extension, which is similar to the more noticeable extension of Greece observed in the Gulf of Corinth [53].

The region's vegetation is highly diverse due to the long-term influence of human activity. The region's vegetation includes high alpine vegetation, mountainous coniferous forests with pine, black pine, and local fir stands, mixed deciduous forests (predominantly oak on the mountain slopes), and scrub vegetation on the exposed limestone [55].

The area's primary natural features include large, mature oak forests on the lower slopes of the mountains, as well as the peaks of Mt. Minthi and western Mt. Tetrazion, which overlook the upper course of the Neda River. This river is renowned for its dramatic waterfalls and steeply carved gorges. The forests on the south side of the Neda River are characterized by high density and lush vegetation, while on the north side they are limited to steep slopes and valleys. In other areas, the forests have been cleared for the cultivation of olives and the construction of agricultural terraces. Oak and chestnut trees are found in the upper regions along the Neda River. Additionally, oak forests are found in protected valleys, including Ampeliona, Agios Sostis, and Petra. Naturalized chestnut trees are found in mixed stands with oaks, and they also grow in isolated, unmixed stands. The cultivation of chestnuts has been encouraged by human intervention, with the resulting harvests being used to produce traditional products in the villages of the area. They are frequently cultivated on agricultural terraces where barley was previously the predominant crop [52–54].

The region is home to a plethora of valuable cultural characteristics that have evolved in parallel with the natural environment. The Park includes a number of significant archeological sites, including the ancient cities of Lykosoura and Trapezous, the sanctuaries of Zeus, Pan, Demeter, and Despoina, the only excavated hippodrome in Greece, and the Temple of Apollo Epikourios, designed by Iktinos, the architect of the Parthenon in Athens (the inaugural UNESCO World Heritage Site in Greece) [54].

3.2. Inventory of Environmental Factors and Processes for Entry to the GPI

The geological hazards selected for consideration in the PHP are landslides (GH1), earthquakes (GH2), weathering (GH3), erosion (GH4), and subsidence (GH5) (Figure 4). These hazards pose a threat to the cultural and natural heritage of the PHP [59]. They can significantly alter its landscape and have the potential to cause significant damage [60]. The environmental factors analyzed in this section are those identified in Section 2 (Figure 4).

3.2.1. Primary Data Acquisition

The primary dataset consists of the following sections 1–10: Information on the data source and the GIS data type are provided in Appendix A.

1. One of the key tools for identifying the environmental factors that contribute to geohazards is the Landsat 8 satellite image of the PHP. The satellite provides multispectral imagery with a spatial resolution of 30 m for most bands, which is particularly useful for capturing a comprehensive view of the landscape while maintaining a balance between detail and coverage. The Landsat 8 satellite acquires data in multiple spectral bands, including the visible, near-infrared, shortwave infrared, and thermal infrared. The extensive range of bands enables the extraction of valuable information on land cover, vegetation health, and surface temperature. The satellite revisits the same area every 16 days, thereby ensuring the regular and consistent collection of data. This temporal resolution is of particular importance for the monitoring of changes over time, particularly in dynamic environments that are susceptible to geohazards [17].
   A satellite imagery-based analytical approach was employed within the QGIS environment to extract key environmental indicators. The Normalized Difference Vegetation Index (NDVI) was calculated to characterize vegetation density across the extensive area of study. Concurrently, the determination of Land Surface Temperature (LST) provided insight into the temperature distribution across the earth's surface. The derived indices, created through the use of geospatial techniques, provide crucial data that can be used to unravel the intricate spatial dynamics of vegetation and surface temperature.
2. Another tool for comprehending topographic variations and evaluating geohazard susceptibility through its high-resolution elevation data is the Global Digital Elevation Model (GDEM). It can be seamlessly integrated with other geospatial datasets, including satellite imagery and geological information. This integration enhances the

understanding of how elevation influences the occurrence and impact of geohazards and provides a comprehensive view of the landscape. The elevation information derived from GDEM is essential for identifying and analyzing environmental factors that contribute to geohazard susceptibility and impact.
An analysis of GDEM data entailing calculations of slope, aspect, slope curvature, and Topographic Wetness Index (TWI) in order to identify the intricate topographic features was undertaken. Slope analysis provided understandings into the steepness of the terrain, while aspect revealed the directional orientation of the slopes. Slope curvature provided valuable information on the curvature characteristics of the landscape. Furthermore, the Topographic Wetness Index, where higher pixel values indicate an increased likelihood of the presence of water, contributed significantly to our understanding of hydrological aspects. These refined terrain descriptors provide insight into deciphering the intricate topographic nuances of the study region. This comprehensive analytical approach significantly enriches our understanding of the complexity of the landscape and makes a substantial contribution to the scientific discourse on environmental studies [24].

3. Lithological data are typically represented as a vector layer in GIS formats. This vector layer contains information on the geological composition of the area of study, including rock types, their distribution, and geological formations. For instance, areas characterized by loose or unconsolidated sediments may be more susceptible to landslides, whereas areas comprising certain types of rock may exhibit greater resistance to erosion. The integration with satellite and imagery data enables researchers to analyze the manner in which geological characteristics interact with topography and land cover to influence the occurrence of geohazards [13,19,30,39].
4. Tectonic structure data are typically represented as a vector layer in GIS formats, highlighting in particular the location and characteristics of fault lines. This vector layer provides crucial information on the presence, orientation, and activity of faults. High-resolution fault data are essential for seismic hazard assessment and for understanding the specific faults that may contribute to earthquakes and associated ground motions [16,26].
5. Land use data are typically represented as a vector layer in GIS formats and categorizes the manner in which land is utilized, including residential, commercial, agricultural, and industrial purposes. These data offer insights into the spatial distribution of human activities. An understanding of land use patterns is essential for the assessment of the contribution of human activities to or mitigation of geohazards. The processes of urbanization, deforestation, agriculture, and infrastructure development can all influence the vulnerability of an area to hazards such as landslides, erosion, and subsidence.
6. Rainfall directly affects hydrological processes, contributing to surface runoff, soil erosion, and slope saturation. Intense or prolonged rainfall events can trigger landslides, flash floods, and other geohazards, particularly in areas with steep terrain. Integrating rainfall data with other environmental datasets, such as topography, soil types, and land use, provides a holistic understanding of how precipitation interacts with the landscape [23,29,32].
7. Rivers play a key role in hydrological processes, influencing water distribution, sediment transport, and soil erosion by transporting sediment downstream. River data help to assess the potential for bank erosion and sediment deposition, which can affect the stability of adjacent slopes and contribute to geohazards.
8. Groundwater affects the stability of subsurface materials and geological formations. Groundwater exerts a profound influence on the stability of subsurface materials and geological formations. A change in the level of groundwater can result in land subsidence, which can in turn affect the stability of infrastructure and landscapes [34].
9. The road network can both contribute to and be impacted by geohazards. The occurrence of slope instability, landslides, and other hazards maximizes a reduction

in the stability of roads, thereby leading to disruptions and potential safety risks. It is therefore important to understand the spatial distribution of roads in order to assess their vulnerability to geohazards.

10. The peak ground acceleration (PGA) is a fundamental parameter for the comprehension of the potential impact of seismic events on structures and landscapes. PGA data indicate the level of ground shaking and are instrumental in assessing the vulnerability of buildings, infrastructure, and natural features to earthquake-induced geohazards. PGA values play a significant role in the development of building codes and seismic design standards. An understanding of the spatial distribution of peak ground acceleration (PGA) enables the implementation of construction practices that can withstand seismic forces, thereby reducing the risk of structural damage during earthquakes. It is reassuring to note that the peak ground acceleration (PGA) in the PHP area is relatively low at 0.16 g −s [16]. A low PGA value indicates a reduced probability of strong ground shaking during seismic events. The lower bound earthquake magnitude represents the threshold below which non-damaging earthquakes are excluded from the hazard analysis. In this study, the threshold is set at a magnitude of 5 for all source zones, as earthquakes below this magnitude are not potentially damaging for well-engineered structures [26,27,57,61].

3.2.2. Data for Information Procedures—Geospatial Analysis

The following advanced geospatial information calculations on the primary data were employed in order to create the appropriate GIS layers:

a. Satellite image processing (zoned vegetation density map (NDVI), zoned land surface temperature (LST) map, zoned map of the Topographical Wetness Index (TWI)).
b. Digital terrain model processing (zoned topography slope map, zoned relief aspect map, zoned map of slope curvature).
c. Lithology processing (zoned lithology map for each geohazard).
d. Faults processing (zoned fault map).
e. Land use processing (zoned land use map).
f. Rainfall—Daily calculations (zoned rainfall map).
g. Surface water processing (zoned river network map, distances from the hydrographic network).
h. Groundwater processing (zoned groundwater map).
i. Calculation of zoned road distance map
j. Zoned PGA map.

The layers of factors involved in geohazard GH1 are introduced below. Similarly, factor layers are calculated for the other five geohazards.

1. Satellite imagery was used to identify environmental indicators while processing data on factors influencing geohazards in the PHP area. The calculation of a vegetation density map involved classifying satellite data to represent different levels of vegetation cover, which was then normalized for standardized assessment. The resulting NDVI raster layer in the GIS platform provided a spatial overview of vegetation health (Figure 11a).
   Layer legend: NDVI indicates whether the target being observed contains live green vegetation or not (resulting values range from −1 to +1). Values close to +1 indicate high vegetation density and health. Values near 0 suggest barren areas of rock, sand, or snow. Negative values indicate water, snow, or clouds.
   The legend represents in color standardized ratings 0–100 for NDVI classes: 0.7–0.53, 0.53–0.36, 0.36–0.19, 0.19–0.02, 0.02−0.15, 0.
   A surface temperature map was also produced using similar classification and normalization procedures, resulting in a Land Surface Temperature (LST) raster GIS layer that captured temperature variations (Figure 11b).
   Layer legend: The LST index represents the temperature of the earth's surface as measured from satellite or ground-based observations. The legend represents in

color standardized ratings 0–100 for LST classes: 24–27.80, 27.80–31.60, 31.60–35.40, 35.40–39.20, 39.20–43.
A Topographic Wetness Index (TWI) map was produced by classifying and normalizing topographic wetness to facilitate understanding of the distribution of moisture across the landscape (Figure 11c).
Layer legend: The TWI is a numerical index that represents the spatial distribution of soil moisture in a landscape, based on its topography. The legend represents in color standardized ratings 0–100 for TWI classes: 22.5–18.38, 18.38–14.26, 14.26–10.14, 10.14–6.02, 6.02–1.9, <1.8.
The processed layers serve as critical inputs for geohazard vulnerability assessment, providing understanding of vegetation health, surface temperature patterns, and topographic wetness characteristics within the study region. The integration of remote sensing techniques enhances the accuracy of environmental assessments and contributes to a comprehensive understanding of the factors influencing geohazard vulnerability.

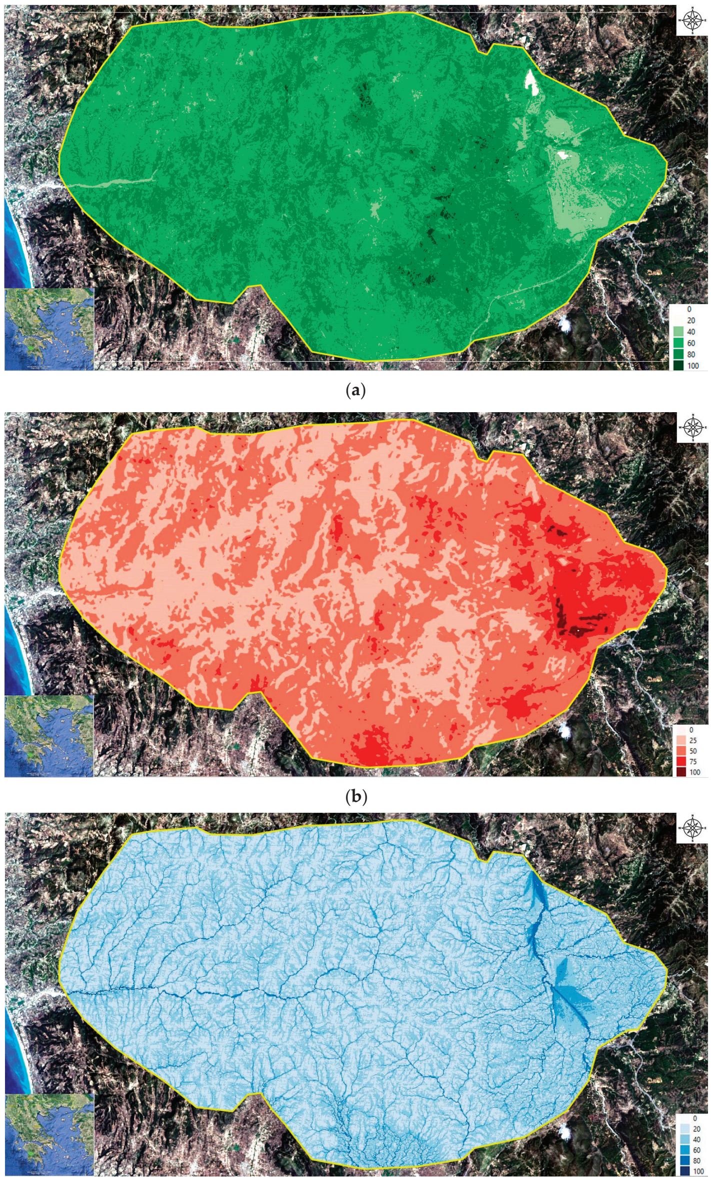
2. The Digital Elevation Model (DEM) was processed to derive topographic features to improve the understanding of terrain characteristics that influence geohazards in the PHP area. To produce a slope map, the DEM was classified to delineate different Slope classes, which were then normalized for standardized presentation. The resulting raster layer provided insight into the variations in terrain steepness (Figure 12a).
Layer legend: The legend represents in color standardized ratings 0–100 for Slope classes, Escarpments, >35, Steep slopes, 25–35, Moderately steep slopes, 15–25, Genie slopes, 5–15, Very gentle slopes, <5.
At the same time, an aspect map was produced, resulting in a raster layer showing terrain orientations. This information helps to identify landscape features that are influenced by slope direction (Figure 12b).
Layer legend: The legend represents in color standardized ratings 0–100 for Aspect classes: >270, 180–270, 90–180, <90.
A curvature map was also produced. The resulting raster layer provides understanding of variations in terrain shape, which helps in the assessment of geological vulnerability associated with curvature characteristics (Figure 12c).
Layer legend: The legend represents in color standardized ratings 0–100 for Curvature classes: <-1.5, -1.5–-0.5, -0.5–0, >0.
These processed maps serve as an essential input to geohazard assessments, providing a comprehensive perspective on the topographic nuances that influence the vulnerability of the region under study to various hazards.
3. Regarding lithology, a careful grouping and ranking of geological formations, assigning values corresponding to each specific geohazard category, is performed. The vector layers representing the lithological formations were then converted into raster layers and normalized to ensure a consistent representation across the area of study (Figure 13). The resulting zoned lithology raster layers provide insight into the spatial distribution and characteristics of geological formations that influence various geohazards.
Layer legend: Assigned values from 0 to 100 to different types of bedrock (lithology map). Lower values indicate a lower risk of landslides, while higher values indicate a higher risk of landslides. Flysch 100, Scree 87.5, Alluvial, Ophiolites 75, Keratolites, Conglomerate rock 62.5, Marls, Clays, Sands 50, Lignite strata, Sandstones 37.5, Limestones, River terraces 25.
4. Focusing on faults, a zoned fault map was produced using a multi-step approach. First, a raster layer was created showing the distance to each fault, which facilitated the assessment of proximity to fault lines. This raster layer was then subjected to classing, normalization, and the construction of a zoned fault map (Figure 14).
Layer legend: The legend represents in color standardized ratings 0–100 for Faults classes: <150 m, 150–300 m, >300 m.

The layer delineates the proximity of faults and provides important insight into the spatial distribution of faults and their potential impact on geohazard susceptibility.

5. Regarding the land use, a zoned map was meticulously calculated. A comprehensive classification and ranking of land use categories on a scale based on their susceptibility to settlement was carried out. Normalization was then applied to standardize the land use values, and the subsequent transformation of four vector layers into raster layers facilitated consistent analysis (Figure 15).
   Layer legend: The legend represents in color standardized ratings 0–100 for Land Use 10 classes, Mineral Extraction sites: 100, Burnt areas: 90—Industrial and Commercial Units, Non-irrigated Arable: 80, Land Road and Rail Networks: 70, Discontinuous Urban Fabric: 60, Transitional Woodland Shrubs: 50, Water bodies: 40, Complex Cultivation Patterns—Principally agriculture with Natural Vegetation, Beaches—Dunes and Sand Plains: 30, Olive Groves—Pastures—Mixed Forest: 20, Broad-leaved Forest—Coniferous Forest—Natural Grassland, Moors, and Heathland—Sclerophyllous Vegetation: 10.
   The resulting zoned land use map provides a structured representation of land use categories, providing insight into the spatial distribution of land cover and its correlation with geohazard susceptibility.
6. As part of the rainfall processing, a zoned rainfall map was created to understand the spatial distribution of precipitation patterns. The process involved the creation of classes categorizing levels of rainfall intensity. Normalization was then applied to ensure consistent representation of rainfall values. The culmination of these steps resulted in the development of a raster layer illustrating zoned rainfall, providing critical understanding to variations in rainfall intensity (Figure 16). This zoned rainfall map is essential for understanding the localized impact of rainfall on geohazards such as landslides and erosion, enabling effective risk assessment and management strategies. Classes 0–1, 1–2, 2–3, 3–4, 4–5 (rainfall).
7. For the surface water data, with a particular focus on rivers, a zoned river map was computed to assess the proximity of rivers. The process began with the conversion and construction of a raster layer mapping the distance to each river. The zoned river map serves as a valuable resource for understanding the relationship between surface water characteristics and geological vulnerability, assisting in the identification of areas prone to river-related geohazards and contributing to targeted risk mitigation strategies.
   With regard to groundwater, a zonal map was also produced to delineate the distribution of underground water sources. The procedure involved the establishment of classes based on groundwater levels, followed by a normalization process to ensure a consistent representation. A raster layer was then generated that provides understanding of the spatial distribution of groundwater resources and highlights their potential impact on landscape dynamics. The zoned groundwater map is proving to be a valuable tool for understanding the complex interplay between groundwater dynamics and the evolving characteristics of the terrain. It helps to identify areas susceptible to groundwater-influenced change and provides a basis for tailored strategies to understand and manage these landscape dynamics.
   A developed zoned map provided a detailed overview of the spatial proximity of road networks across the PHP area. The process began with the conversion and construction of a raster layer that recorded the distance from each road. The raster layer was then categorized and normalized, culminating in the creation of a zoned road network map. The layer provides an understanding of the influence of road networks on the surrounding terrain. The zoned road network map is proving to be a key tool for unraveling the impacts of transport networks, helping to identify regions shaped by road infrastructure, and contributing to land-use planning strategies.
   As part of the PGA processing, the analysis produced a zoned map detailing the maximum ground acceleration across the PHP. A raster layer was generated showing

the zoned map of maximum ground acceleration with the values standardized accordingly. This map provides understanding of the varied spatial distribution of ground acceleration, thus providing a detailed perspective on seismic characteristics as required by GreDaSS [62]. The zoned PGA map is a valuable tool for understanding the diverse seismic conditions within the area of study, providing valuable information for strategic decision-making in infrastructure development and seismic risk mitigation.

In the following figures, the park boundary is represented by the yellow polygonal line.

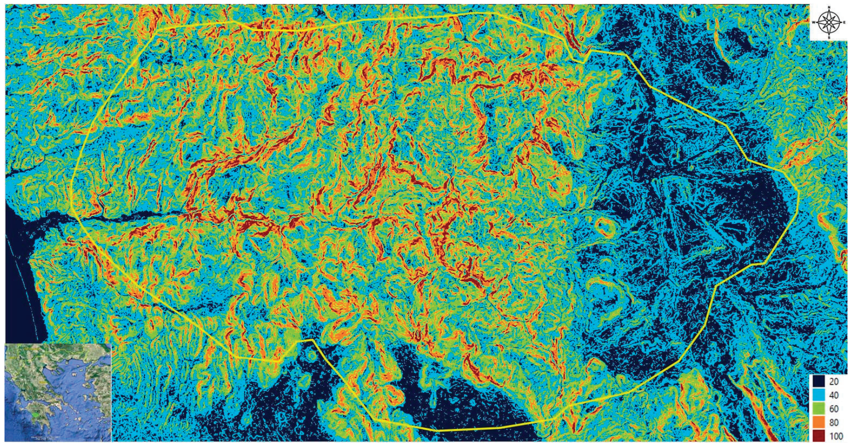


(a)

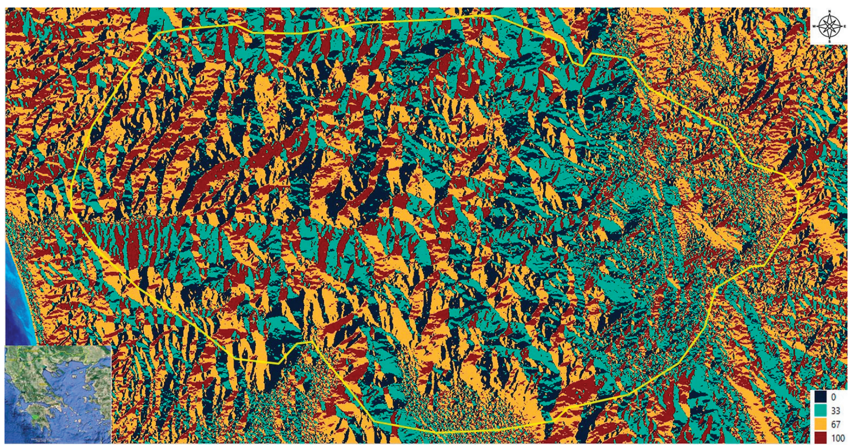
(b)

(c)

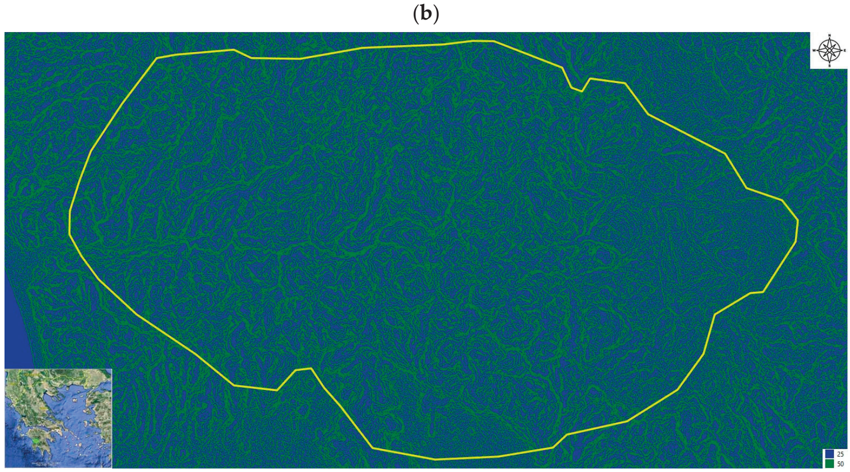
Figure 11. (**a**) NDVI raster layer. (**b**) Land Surface Temperature (LST) raster layer. (**c**) Topographic Wetness Index (TWI) raster layer.



(a)



(b)



(c)

Figure 12. (**a**) Slope raster layer. (**b**) Aspect raster layer. (**c**) Curvature raster layer.

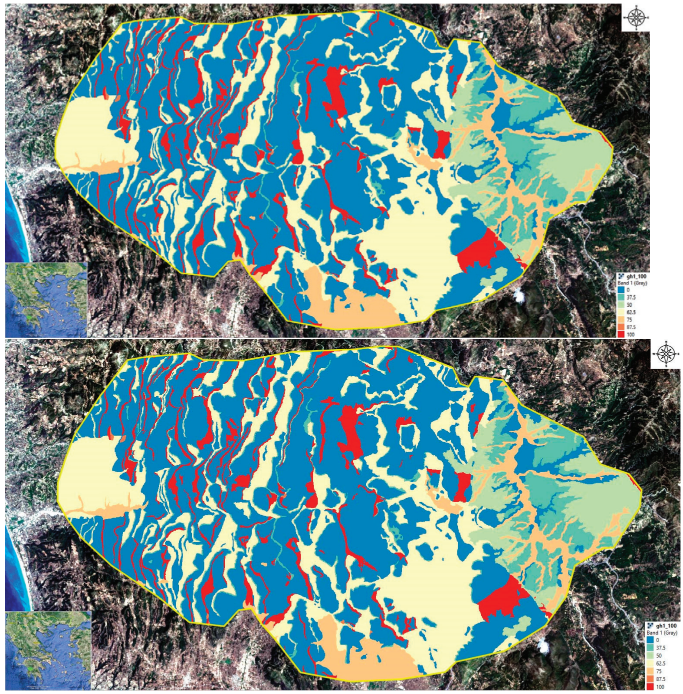


Figure 13. Lithology raster layer.

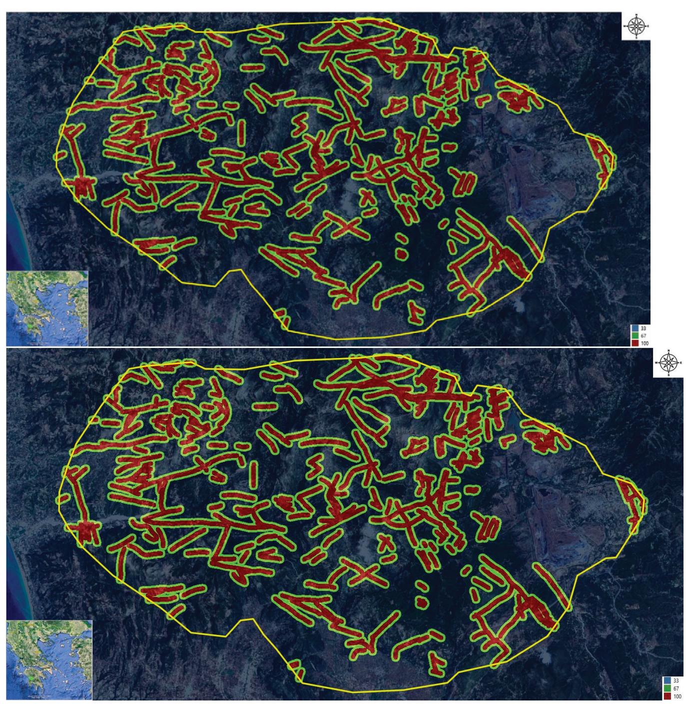


Figure 14. Faults raster layer.

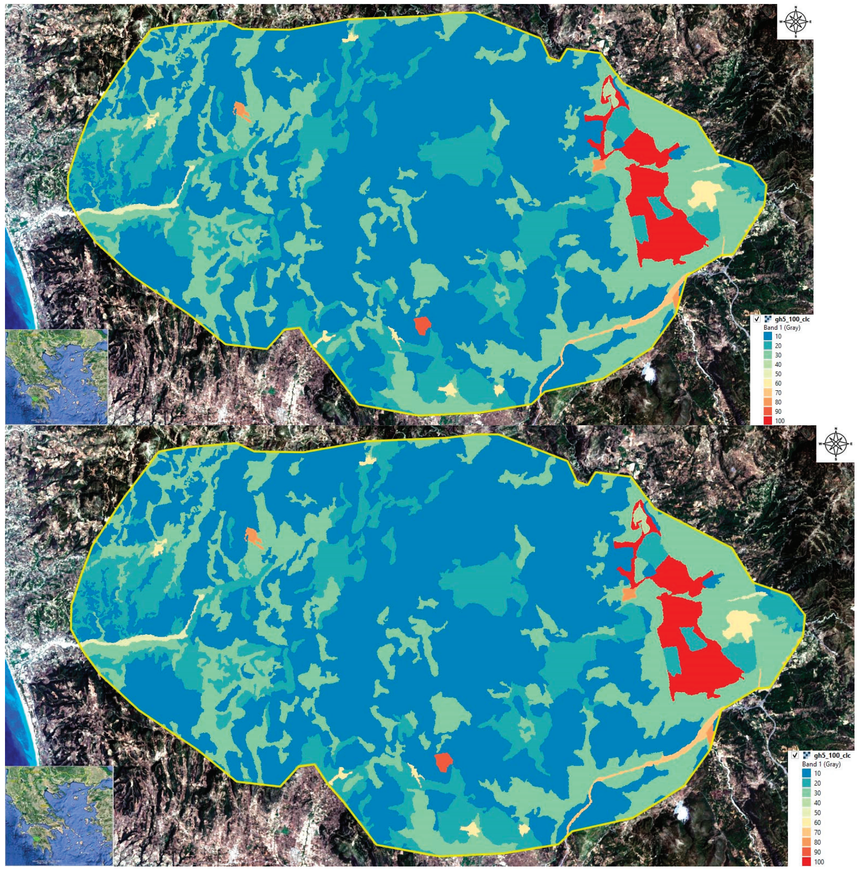


Figure 15. Land-use raster layer.

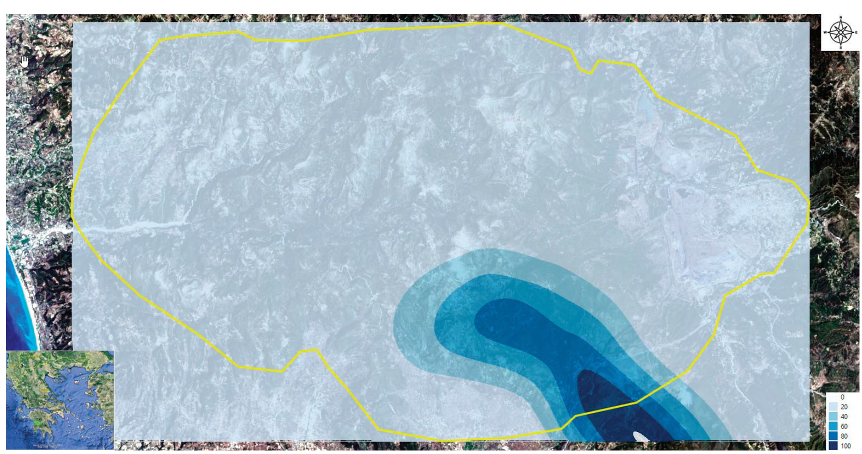


Figure 16. Rainfall (summer data) raster layer.

3.3. Geohazards Prevention Index (GPI) Implementation

The GPI is initiated at two distinct phases. At the initial phase, geohazard maps are calculated on a geohazard-by-geohazard basis. Each geohazard, as described in the framework's functions C, D, and E, is the sum of the environmental factors contributing to each geohazard multiplied by the weight of their contribution to it. The weights are calculated using the AHP method. The calculated raster layers of each geohazard are then stored on the GIS platform. In the second and final phase, the cumulative geohazard is calculated as the sum of the previously calculated hazards for each geohazard, multiplied by the weight of each hazard's participation. The weights are substituted once more by applying the AHP method.

3.3.1. Generation of Zoned Hazard Map per Geohazard

Analytic Hierarchy Process (AHP) is an advanced scoring method that can be used to determine the relative importance and influence of each factor, in our case in the context of each geohazard. The method uses a series of pairwise comparisons to assess the importance of factors and determine their weights. It systematically assesses the relative importance of factors by considering all possible pairs and determining their importance in a consistent manner. By comparing factors based on a set of criteria, AHP allows the generation of weighted values that reflect the hierarchy and relative influence of each factor within the overall analysis.

The importance of each pairwise comparison in the method, in the case of PHP, was determined based on both an extensive review of the relevant literature and consultation with recognized experts in the field (interviewing geologists from the Kapodistrian University of Athens, the University of West Attica, and the University of Patras). With this knowledge, the comparison criteria were carefully evaluated to ensure a robust and informed assessment of the relative importance of the factors [12,40].

The calculations of the AHP method were performed using the original software of Spicelogic Inc., version 4.2.6.

(a) Below are the results of the method, presented with three figures for each geohazard. The first one in each set shows the Pairwise Comparison Matrix of the AHP. This matrix is of crucial importance, as it converts subjective assessments into a mathematical form, thereby enabling a systematic and objective decision-making process. It ensures that all criteria and alternatives are considered relative to one another and provides a method for verifying the consistency of these comparisons, thereby leading to more reliable and justifiable decisions.
The consistency ratio (CR) displayed in each figure is calculated to ensure that the comparisons are sufficiently consistent. A CR of less than 0.1 is generally considered acceptable. High inconsistency indicates the need for re-evaluation of the comparisons [40].
The calculations for the geohazards (GH), landslide (Figure 17), weathering (Figure 18), erosion (Figure 19), and subsidence (Figure 20) show very good CR values, so there is no need to recalculate the pairs.
(b) The second figure of the triad shows the relative priority of each factor involved in the formation of the geohazard in percentages.
(c) Finally, the third figure shows the calculated weights.

Priority Trade-offs

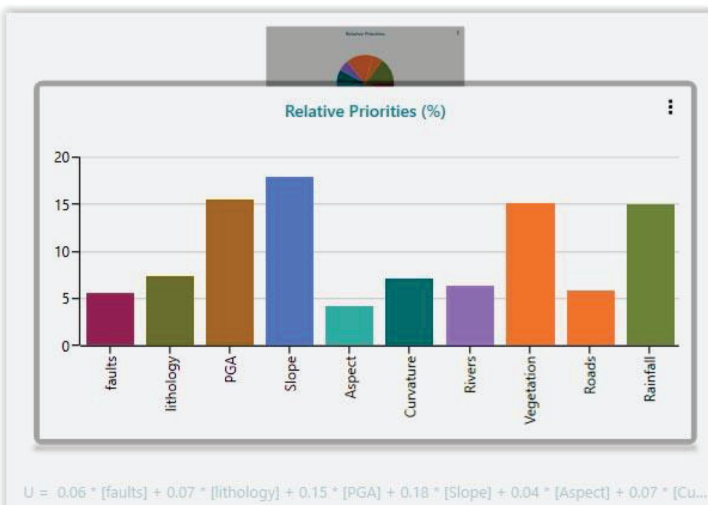
Matrix View

	faults	lithology	PGA	Slope	Aspect	Curvature	Rivers	Vegetation	Roads	Rainfall	Priorities
faults	1	2	0.25	0.2	0.5	0.5	0.5	0.5	2	0.5	0.056
lithology	0.5	1	0.333	0.333	2	1	2	0.5	3	0.5	0.074
PGA	4	3	1	0.5	4	2	2	0.5	4	2	0.155
Slope	5	3	2	1	3	2	3	0.5	3	2	0.178
Aspect	2	0.5	0.25	0.333	1	0.5	0.5	0.333	0.333	0.25	0.042
Curvature	2	1	0.5	0.5	2	1	2	0.5	0.5	0.333	0.072
Rivers	2	0.5	0.5	0.333	2	0.5	1	0.5	2	0.333	0.064
Vegetation	2	2	2	2	3	2	2	1	2	0.5	0.151
Roads	0.5	0.333	0.25	0.333	3	2	0.5	0.5	1	0.333	0.059
Rainfall	2	2	0.5	0.5	4	3	3	2	3	1	0.149

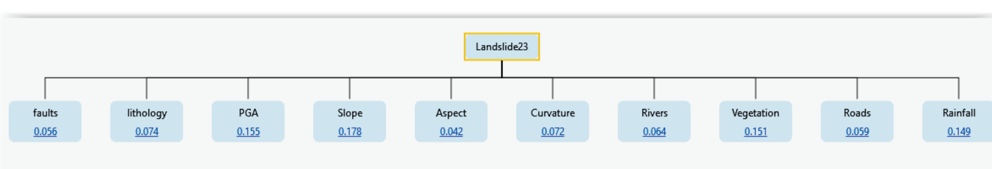
Enforce Transitivity Rule

Consistency Ratio = 0.0815

(**a**)



(**b**)



(**c**)

Figure 17. (**a**) Landslide Geohazard Pairwise AHP matrix. (**b**) Landslide AHP Relative Priorities diagram. Landslide: 0.06 × [faults] + 0.07 × [lithology] + 0.15 × [PGA] + 0.18 × [Slope] + 0.04 × [Aspect] + 0.07 × [Curvature] + 0.06 × [Rivers] + 0.15 × [Vegetation] + 0.06 × [Roads] + 0.15 × [Rainfall]. (**c**) Landslide AHP weight calculations: Faults 0.056, Lithology 0.074, PGA 0.155, Slope 0.178, Aspect 0.042, Curvature 0.072, Rivers 0.064, Vegetation 0.151, Roads 0.059, and Rainfall 0.149.

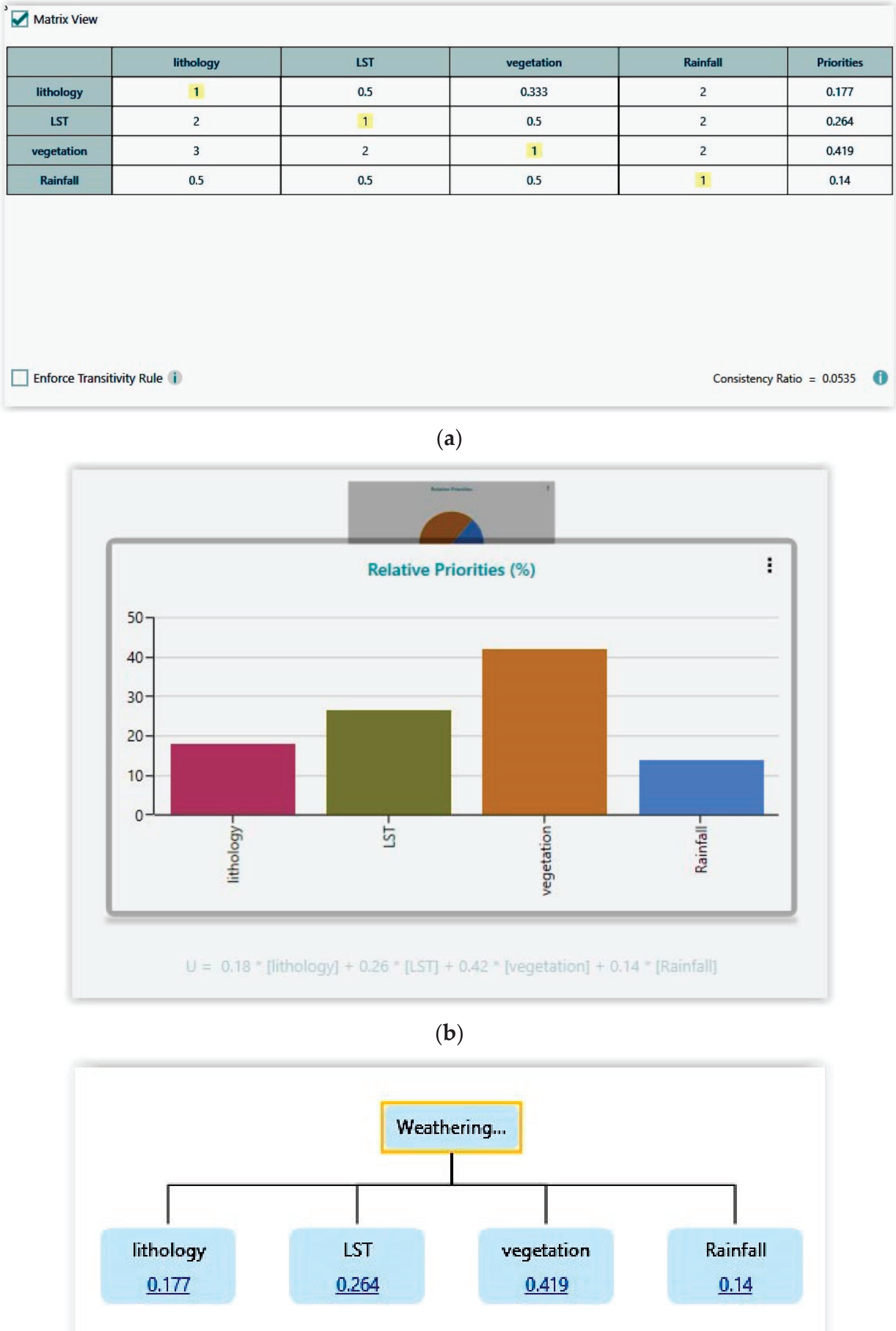
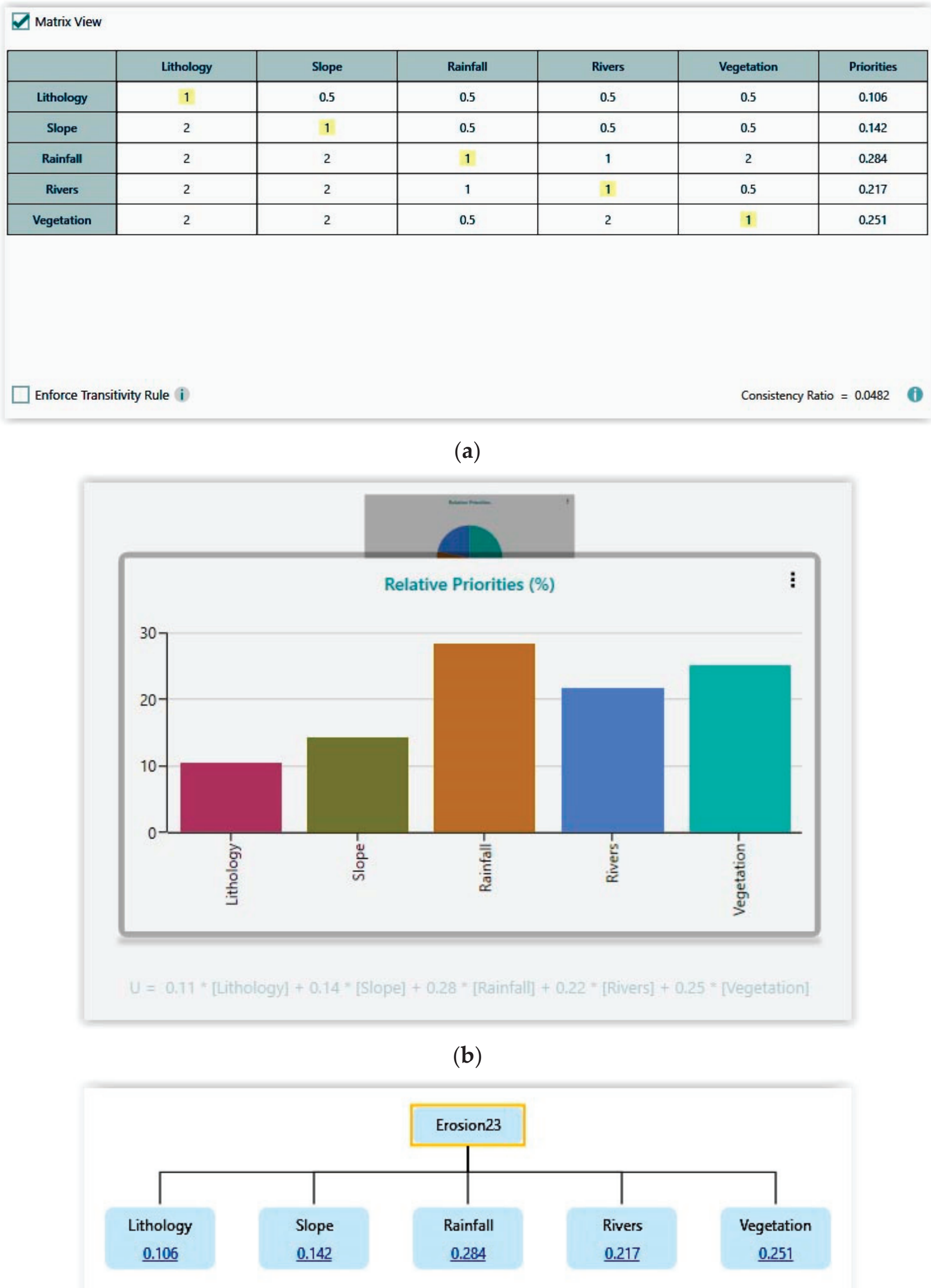


Figure 18. (**a**) Weathering Geohazard Pairwise AHP matrix. (**b**) Weathering AHP Relative Priorities diagram. Weathering: 0.18 × [lithology] + 0.26 × [LST] + 0.42 × [vegetation] + 0.14 × [Rainfall]. (**c**) Weathering AHP weight calculations.



Matrix View

	Lithology	Slope	Rainfall	Rivers	Vegetation	Priorities
Lithology	1	0.5	0.5	0.5	0.5	0.106
Slope	2	1	0.5	0.5	0.5	0.142
Rainfall	2	2	1	1	2	0.284
Rivers	2	2	1	1	0.5	0.217
Vegetation	2	2	0.5	2	1	0.251

Enforce Transitivity Rule

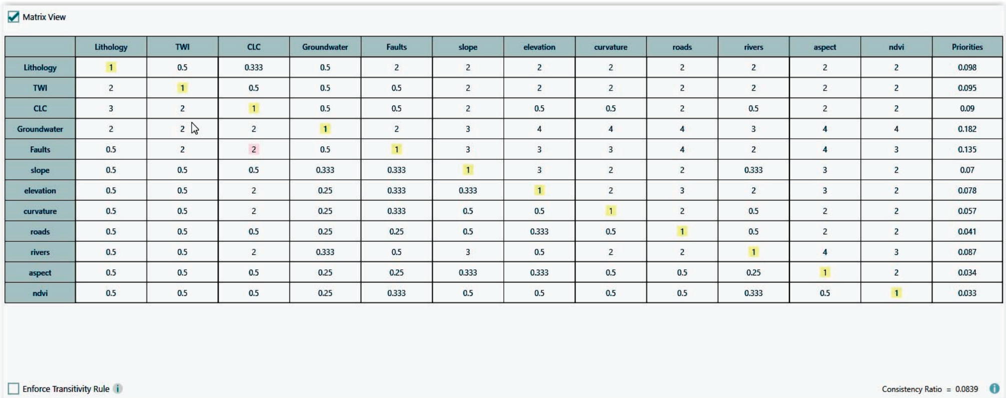
Consistency Ratio = 0.0482

(**a**)

(**b**)

(**c**)

Figure 19. (**a**) Erosion Geohazard Pairwise AHP matrix. (**b**) Erosion AHP Relative Priorities diagram. Erosion: 0.11 × [Lithology] + 0.14 × [Slope] + 0.28 × [Rainfall] + 0.22 × [Rivers] + 0.25 × [Vegetation]. (**c**) Erosion AHP weight calculations.



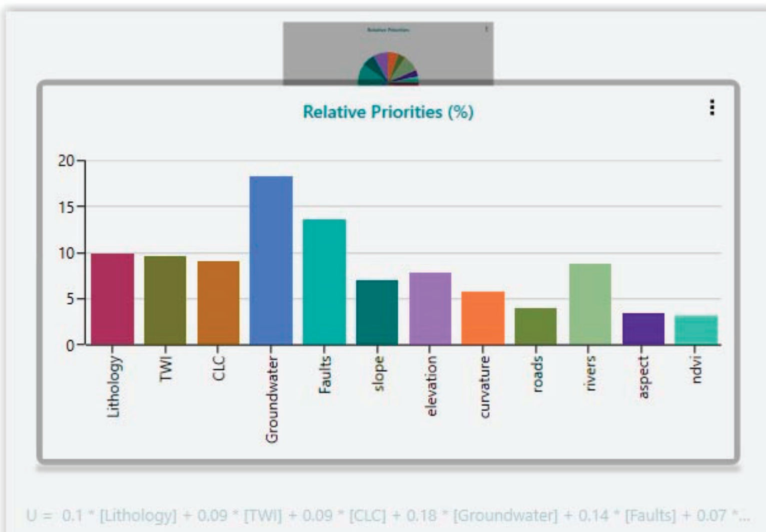
Matrix View

	Lithology	TWI	CLC	Groundwater	Faults	slope	elevation	curvature	roads	rivers	aspect	ndvi	Priorities
Lithology	1	0.5	0.333	0.5	2	2	2	2	2	2	2	2	0.098
TWI	2	1	0.5	0.5	0.5	2	2	2	2	2	2	2	0.095
CLC	3	2	1	0.5	0.5	2	0.5	0.5	2	0.5	2	2	0.09
Groundwater	2	2	2	1	2	3	4	4	4	3	4	4	0.182
Faults	0.5	2	2	0.5	1	3	3	3	4	2	4	3	0.135
slope	0.5	0.5	0.5	0.333	0.333	1	3	2	2	0.333	3	2	0.07
elevation	0.5	0.5	2	0.25	0.333	0.333	1	2	3	2	3	2	0.078
curvature	0.5	0.5	2	0.25	0.333	0.5	0.5	1	2	0.5	2	2	0.057
roads	0.5	0.5	0.5	0.25	0.25	0.5	0.333	0.5	1	0.5	2	2	0.041
rivers	0.5	0.5	2	0.333	0.5	3	0.5	2	2	1	4	3	0.087
aspect	0.5	0.5	0.5	0.25	0.25	0.333	0.333	0.5	0.5	0.25	1	2	0.034
ndvi	0.5	0.5	0.5	0.25	0.333	0.5	0.5	0.5	0.5	0.333	0.5	1	0.033

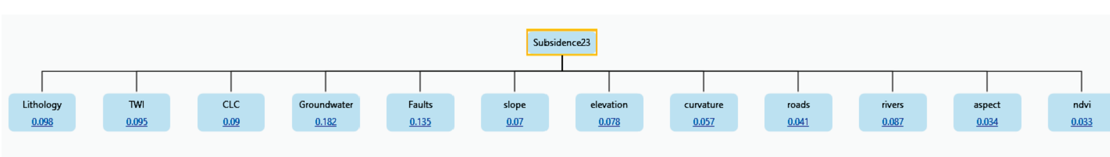
Enforce Transitivity Rule

Consistency Ratio = 0.0839

(**a**)



(**b**)



(**c**)

Figure 20. (**a**) Subsidence Geohazard Pairwise AHP matrix. (**b**) Subsidence AHP Relative Priorities diagram. Subsidence: 0.1 × [Lithology] + 0.09 × [TWI] + 0.09 × [CLC] + 0.18 × [Groundwater] + 0.14 × [Faults] + 0.07 × [slope] + 0.08 × [elevation] + 0.06 × [curvature] + 0.04 × [roads] + 0.09 × [rivers] + 0.03 × [aspect] + 0.03 × [ndvi]. (**c**) Subsidence AHP weight calculations: Lithology 0.098, TWI 0.095, CLC 0.09, Groundwater 0.182, Faults 0.135, Slope 0.07, Elevation 0.078, Curvature 0.057, Road Network 0.041, Rivers 0.087, and Aspect 0.034, NDVI 0.033.

3.3.2. Generation of Cumulative Geohazard Zoned Map

The weighted contribution of geohazards to the Geohazards Prevention Index (GPI) was once again calculated using the Analytic Hierarchy Process (AHP) method [40]. This involved an exhaustive pairwise comparison of the geohazards, taking into account their relative importance in the context of the GPI. As previously, the importance of each pairwise comparison in the method in the case of the PHP was determined again. The calculated CR is highly satisfactory (Figure 21). The AHP facilitated a systematic evaluation of the geohazards by assigning weights based on their hierarchical importance. The method provided a comprehensive understanding of the individual contributions of geohazards to the overall GPI.

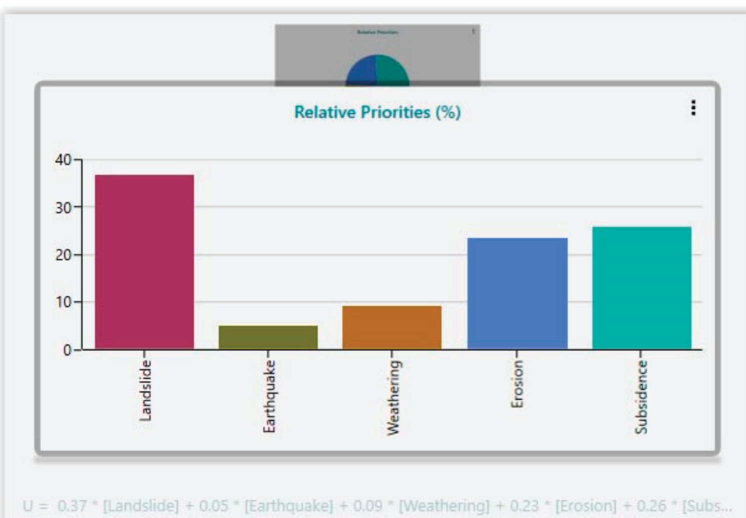
Matrix View

	Landslide	Earthquake	Weathering	Erosion	Subsidence	Priorities
Landslide	1	6	4	3	1	0.365
Earthquake	0.167	1	0.333	0.333	0.2	0.051
Weathering	0.25	3	1	0.333	0.25	0.092
Erosion	0.333	3	3	1	2	0.235
Subsidence	1	5	4	0.5	1	0.257

Enforce Transitivity Rule

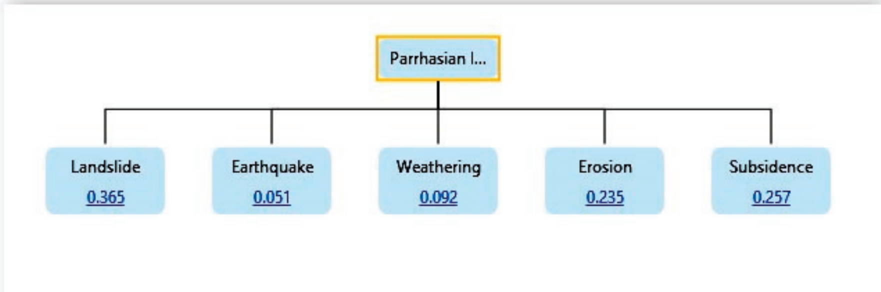
Consistency Ratio = 0.0830

(**a**)



(**b**)

Figure 21. *Cont.*



(**c**)

Figure 21. (**a**) Cumulative Geohazards Pairwise AHP matrix. (**b**) Cumulative Geohazards AHP Relative Priorities diagram. GPI: 0.37 × [Landslide] + 0.05 × [Earthquake] + 0.09 × [Weathering] + 0.23 × [Erosion] + 0.26 × [Subsidence]. (**c**) Cumulative Geohazards AHP weight calculations.

The Geohazards Prevention Index (GPI) was employed to generate the Cumulative Geohazard Assessment Map, presented in Figure 22, of the Parrhasian Heritage Park of the Peloponnese.

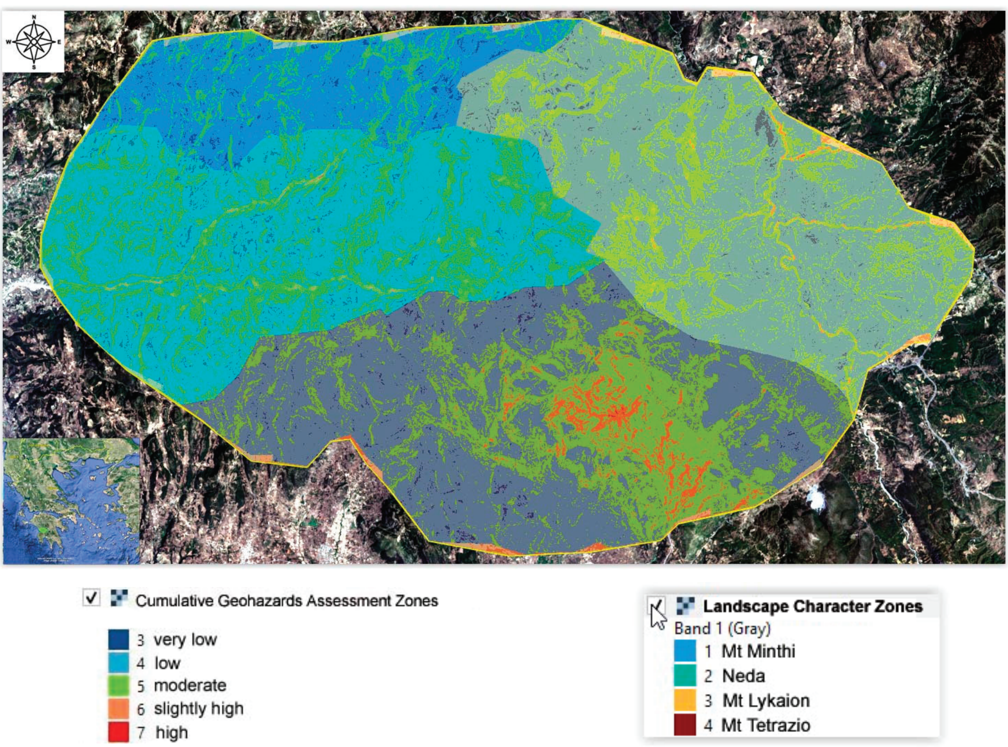
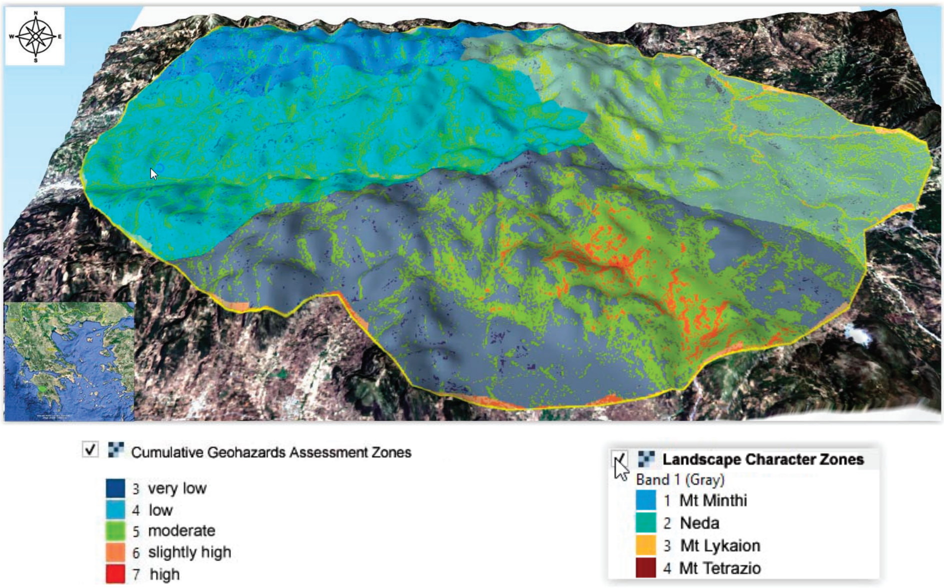


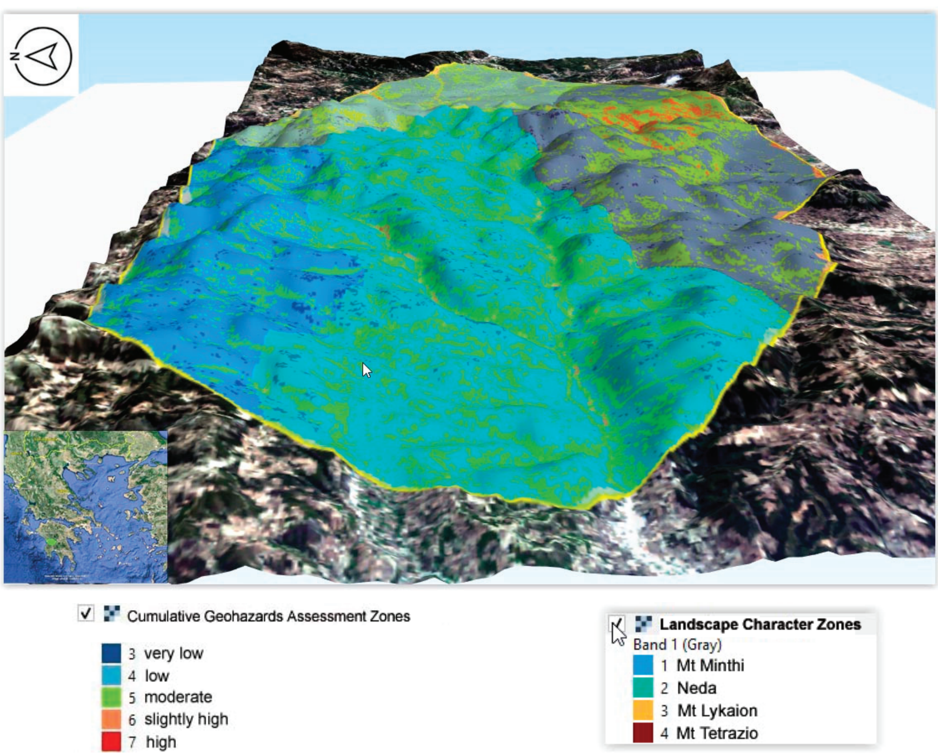
Figure 22. Parrhasian Heritage Park—Cumulative Geohazard Assessment Map.

Legend: 1—Insignificant; 2—Extremely Low; 3—Very Low; 4—Low; 5—Moderate; 6—Slightly High; 7—High; 8—Very High; 9—Extremely High; and 10—Critically High [42].

Figure 23 presents two three-dimensional views of the Cumulative Geohazard Assessment Map.



(**a**)



(**b**)

Figure 23. Parrhasian Heritage Park—Cumulative Geohazard Zoned Map. (**a**) Three-dimensional view from south Mt. Tetrazio landscape zone. (**b**) Three-dimensional view from west Neda and Mt. Minthi landscape zones.

In Figure 23a the distinctive relief of the four landscape character zones is depicted. The mountainous zone of Mt. Minti (zone 1) in the north and the mountainous zone of Mt. Tetrazion in the south (zone 4) collectively form an envelope that encloses the Mt. Lykaion Zone (zone 3) in the east and the Neda Zone (zone 2) in the west.

This envelope is characterized by an extraordinary gorge with the Neda River that leads to the west, at the Kyparissiakos Gulf.

Figure 23b is eastward oriented, and the full expanse of the Neda River gorge is visible. The characteristic mountainous envelope is also evident in the image.

3.3.3. Validation of Results (ROC Analysis)

The evaluation of the GPI was based on the Receiver Operating Characteristic (ROC) analysis. This is a powerful and widely used method for evaluating the performance of binary classification models. It is particularly useful for understanding the trade-offs between true positive rates (sensitivity) and false positive rates (specificity) at different threshold settings.

The visual output of the application is the ROC curve, a graphical plot that illustrates the diagnostic ability of the binary classifier system. It is generated by plotting the true positive rate against the false positive rate at various threshold settings. Each point on the ROC curve represents a sensitivity/specificity pair corresponding to a particular decision threshold [43].

In the graph (Figure 24), the x-axis represents the false positive rate, which is the percentage of true negatives that are incorrectly identified as positives by the model. The y-axis represents the true positive rate (sensitivity), which is the percentage of true positives correctly identified by the model. For specific geohazard points on the Cumulative Geohazard Zoned Map, the ground situation was observed.

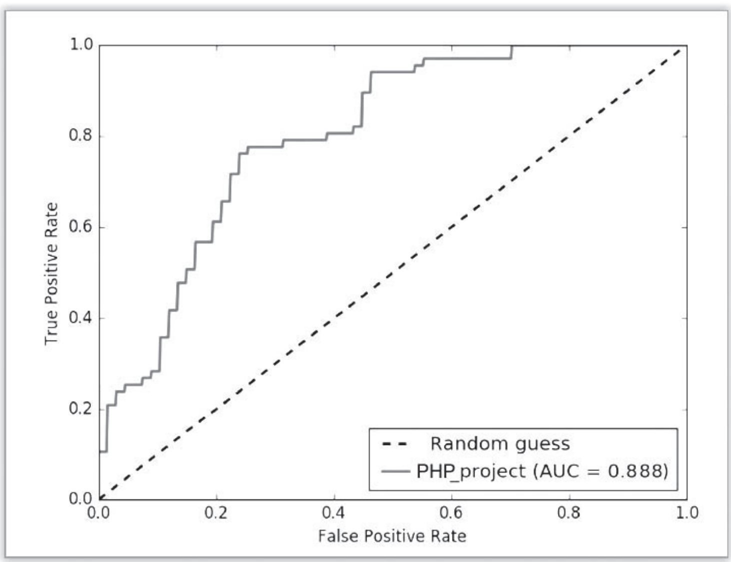


Figure 24. ROC curve—PHP.

The generated curve displays the area under the curve (AUC). The AUC represents the degree or measure of separability achieved by the model. It quantifies the overall ability of the model to discriminate between positive and negative classes. AUC values range from 0 to 1. For AUC = 1, we have a perfect model that correctly classifies all positive and negative cases. For AUC = 0.5, we have a model with no discriminative ability, equivalent to a random guess. For AUC < 0.5, we have a model that performs worse than random guessing, indicating a poor classifier.

The reliability of the cumulative geohazard map has been tested using the ROC method in the QGIS environment with the SZ plugin, which is an open source tool. Feature points were selected across the PHP area, in each landscape character zone, of selective cumulative geohazard zones, which were verified by field survey. ROC analysis yielded an AUC with a value of 0.888. The final result demonstrates a highly satisfactory operation of the GPI [43,63].

3.4. Spatial Identifications for Geohazard Prevention

The final zoned cumulative geohazard map provides the means to spatially identify critical sub-zones and the locations of heritage features within them (Figure 25). The delineation and identification of these entities was achieved by combining the geohazard prevention zones with the landscape character zones. This was carried out by assigning to each sub-zone both the landscape character with its heritage features and the significance of the cumulative geohazard that threatens it. The dual identity of the sub-zones, as well as their content, provide indications for early prevention with targeted actions. These indications answer the question of what is likely to happen and where it is going to happen, with the objective of reducing or preventing such occurrences.

The results demonstrate the capacity of the tool to identify spatial units of varying graded geohazards. The geohazard zones in the PHP that are potentially most endangered are presented in more detail below.

As evidenced by the case of the Framework application in the PHP, sub-zones of considerable geohazard importance are observed over a vast area in landscape character zone Mt. Tetrazion, as well as in a limited area in the Mt. Lykaion LCZ. Sub-zones of notable importance are distributed across a significant portion of the Mt. Tetrazion LCZ, Mt. Lykaion LCZ, and Neda LCZ. It is also observed that heritage features are included in or are close to these sub-zones. It is crucial to note the importance of the heritage features contained in each sub-zone, as well as the size of the area it covers. It should also be stressed that they are not always observed in proportion. For example, there may be few valuable features that need prevention in a large spatial coverage of high geohazards. Indicative sub-zones are pictured in black polygons in Figure 25.

In the Mt. Tetrazio LCZ, located to the south of the villages of Isari and Vasta and to the east of the sanctuary and temple at Melpia, the cumulative geohazard is classified as grade 6 to 7 (on a ten-point scale, as previously outlined in the text). In the same LCZ, to the east of the ancient city of Trapezous, a geohazard zone of grade 6 is observed.

In the Neda LCZ, specifically in the area of Vasses and to the south of Linistaina village on the Neda tributary, the geohazard index reaches grade 6. In the village of Kakaletri, situated in close proximity to the ancient town of Eira, the geohazard index has been determined to be at grade 6. Additionally, a grade 6 index is observed in the region south of Figalia and the temple of Athena and Zeus in Figalia.

In areas where geohazard grades 6 and 7 (slightly high and/or high) are prevalent, there is an urgent need for further in situ studies. As can be observed, the intensifying phenomena of climate change are resulting in a reduction in overall rainfall but an increase in the intensity of precipitation events. The occurrence of high rainfall rates in a relatively short period of time, coupled with the presence of prolonged periods of high temperatures (i.e., during drought conditions), can lead to an increase in geohazards, such as weathering and erosion. This, in turn, can result in the occurrence of landslides and subsidence, which can further magnify the observed phenomenon.

In the specific context of the area of interest, the contribution of each geohazard to the cumulative geohazard is as follows: 36.5% landslide, 5.1% earthquake, 9.2% weathering, 23.5% erosion, and 25.7% sedimentation. These figures are based on the given climatic conditions (summer with variable rainfall) and the existing state of the natural environmental factors.

Consequently, in order to ascertain the relationship between geohazards and landscapes containing sensitive features of cultural and natural heritage, it is necessary to implement a focused planning strategy involving comprehensive surveys and in situ studies, with the objective of achieving sustainable management [64–66].

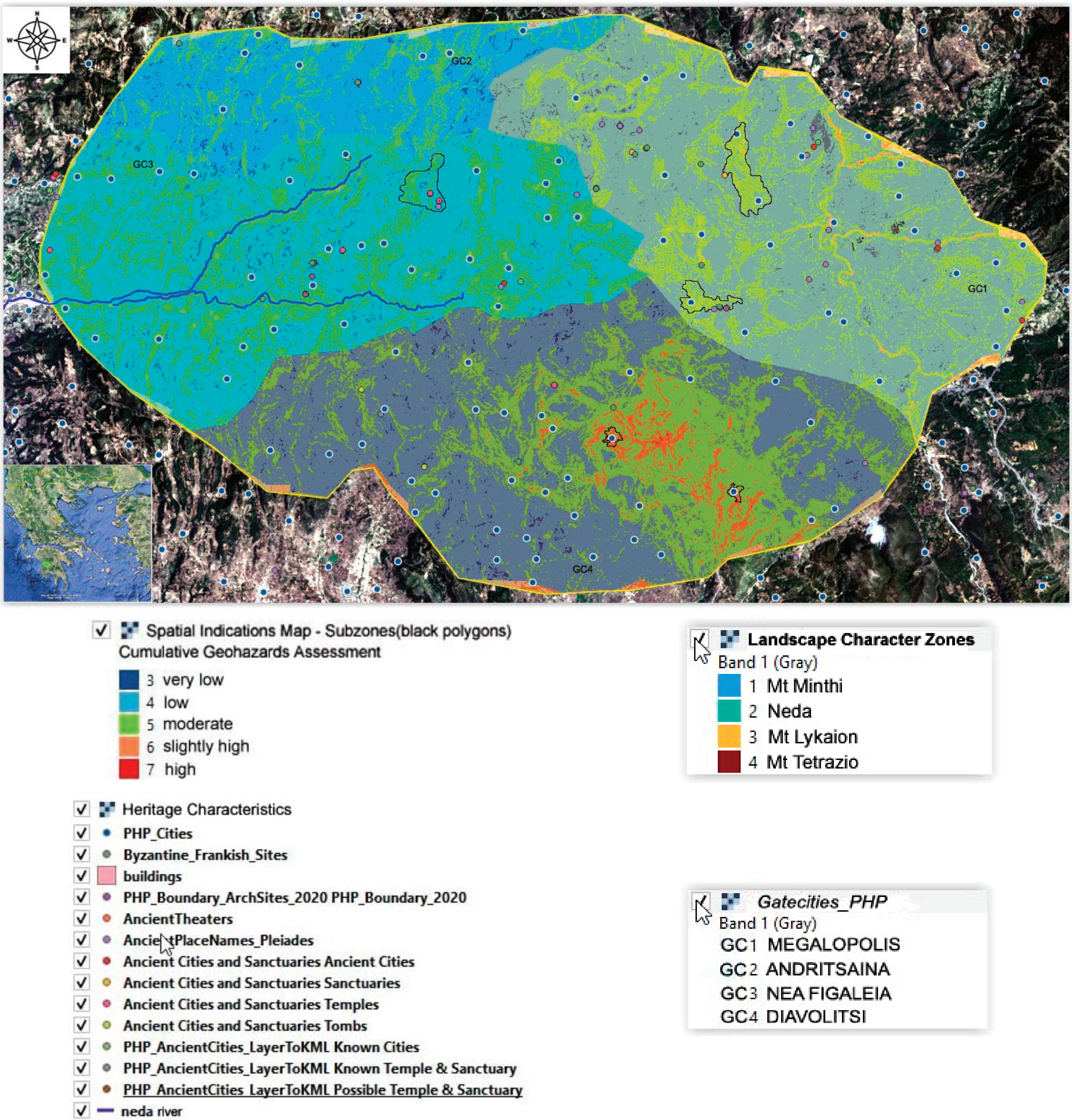


Figure 25. Spatial identification map for geohazard prevention.

4. Discussion

The proposed methodological framework places significant emphasis on the importance of prevention, thus the pre-management stage of cultural and natural heritage areas. In these areas, the environmental factors that contribute to the occurrence of geohazards assume a distinct role with respect to the protection of their heritage features, compared to the factors and geohazards present in other areas. Hence, the framework is specifically designed to facilitate early prevention by taking into account the factors and their degree of involvement in the development of geohazards. The framework is based on a cumulative approach to geohazard assessment and considers not only the individual geohazards present in the area but also the collective impact of all geohazards on the cultural and natural heritage landscape.

Previous research internationally has mainly dealt with the assessment of one geohazard at a time, mainly concerning landslides and earthquakes. There is no specific focus on cultural and natural heritage sites, which have sensitive heritage features that require timely and detailed investigation for their protection.

A limitation of focusing on a single geohazard is that it fails to consider the full range of potential geohazards, which may result in an incomplete understanding of the impacts posed by geologic phenomena. This approach presents a number of significant disadvantages. It may result in the inadvertent overlooking of other potential threats. For instance, in the context of earthquake preparedness, the one-hazard approach may neglect to consider the potential risks associated with landslides. Conversely, this approach may result in an erroneous assumption of protection. It is evident that areas of cultural and natural heritage are susceptible to a multitude of geohazards that have yet to be assessed. It is conceivable that the implementation of mitigation measures for one geohazard may not address and could even exacerbate the risks associated with other geohazards. Moreover, there is an increased vulnerability and a lack of comprehensive preparedness. A narrow focus on a single geohazard may result in an incomplete understanding of the potential for that geohazard to trigger another. Heavy precipitation can precipitate landslides, which may not be considered if the study in question focuses exclusively on rainfall. In general, the protection of a heritage landscape through the study of a single geohazard can result in significant vulnerabilities, an inefficient use of resources, and an inadequate preparedness and response strategy.

Thus, it is apparent that a cumulative geohazard approach is indispensable for the prevention and preservation of the heritage landscape. The principal advantages of a cumulative approach include a more comprehensive understanding of preparedness, improved mitigation, enhanced decision-making, increased awareness, and long-term sustainability. In the context of climate change, cumulative assessments are of particular importance, as they can identify how changing environmental conditions may influence the frequency and severity of geohazards. This approach encourages interdisciplinary collaboration, facilitating the development of innovative solutions and enhanced predictive models. The application of advanced technologies, including geographic information systems (GIS), remote sensing, and big data analytics, can enhance the accuracy and comprehensiveness of cumulative geohazard assessments.

Therefore, the cumulative approach to geohazard assessment facilitates a more comprehensive understanding of the upcoming threats, ultimately contributing to the protection of heritage landscapes and their resilient communities.

5. Conclusions

The findings of the research indicate that by utilizing the proposed methodological framework and the GPI in accordance with their intended specifications, critical questions can be answered. These include whether the framework is a prevention tool, whether it is usable, whether it is technologically up to date, whether it is economical to use, whether it provides spatial information, and finally, whether it is effective.

The process is one of reconnaissance, which enables the timely anticipation of the evolution of cumulative geohazards. The implementation of the methodological framework is subject to the specific conditions of the natural environment in the area of interest. Furthermore, it may be applied on a daily basis in instances where intensifying phenomena are observed in the area as an impact of climate change. The framework's index is designed to accommodate the distinctive characteristics of each region. The prevention framework is a useful and rapid tool that operates in a modern technological environment. It is based on spatial analysis and requires no cost to operate, utilizing digital information and techniques. Its utility lies in the capacity to early inform decision-making processes regarding effective and responsible environmental management.

The contribution of this research is evident in the creation of such a methodological framework for geohazard prevention, which introduces a new index for assessing geohazards that threaten heritage landscapes. These landscapes are more sensitive and therefore require special attention and preparedness to reduce the impact of geohazards. The structure of the index is based on an innovative approach—the cumulative approach. It emphasizes the spatial dimension by using new technologies and working in a GIS environment. The index provides the opportunity to identify the most significant environmental factors associated with geohazards and the relationships between all geohazards. It also allows for the comprehension of the contribution of multiple parameters to the genesis of geohazards and the interpretation of the generation mechanisms and processes of their occurrence. This is accomplished by employing data investigations, analytical processes, and the interpretation of the acquired information pertinent to the specific area.

As previously indicated, the framework and the index are intended for application to terrestrial cultural and natural heritage areas. Hence, a future research development would be an analysis of geohazards and their environmental factors in heritage areas affected by the sea. Subsequently, the index will be expanded to include new terms and weights. It should be noted that the framework and its index cannot be applied to any area; they address the assessment of geohazards in cultural and natural heritage landscapes.

As this tool will contribute to the sustainable management of these areas, the implications of its utilization can be summarized as follows: It indicates spatial designations for actions to mitigate or even prevent the evolution of geohazards, which by their very nature require local studies. Subsequently, the tool addresses the conservation of valuable and sensitive landscapes and their features, with the objective of enhancing them where necessary. Ultimately, this tool facilitates the reduction in time and financial expenditure associated with unnecessary and costly actions, thereby advancing the sustainable management of cultural and natural heritage landscapes.

Overall, this geohazard assessment approach serves to highlight the necessity of acquiring the requisite knowledge to adopt preventive measures and site-specific mitigation strategies in a timely manner, thereby preventing the acceleration of geohazards into disasters. Furthermore, it serves to highlight the necessity of protecting landscapes with cultural and natural heritage characteristics for future generations.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Information on the data source and the GIS data type:

- Landsat 8 satellite image (Source: USGS)
- Digital terrain model (Data type: raster layer)
- Lithology data (Source: Hellenic Geological and Mineral Exploration Authority, Data type: vector layer)

- Faults data (Source: Hellenic Geological and Mineral Exploration Authority, Data type: vector layer)
- Land use data (Source: Copernicus, Data type: vector layer)
- Rainfall data (Source: Hellenic National Meteorological Service, Data type: vector layer)
- Surface water data (Source: geodata.gov.gr, Data type: vector layer)
- Groundwater data (Source: geodata.gov.gr, Data type: vector layer)
- Road Network data (Source: geodata.gov.gr, Data type: vector layer)
- Peak Ground Accelerator data (Source: GreDaSS, Data type: vector layer)
- Cultural characteristics (Source: National Monuments Archive, 2023, Ministry of Culture, vector layer).

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Article

Sensory Responsive Environments: A Qualitative Study on Perceived Relationships between Outdoor Built Environments and Sensory Sensitivities

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Abstract: This qualitative study explored the perceived relationships between outdoor built environments and sensory sensitivities, focusing on autism, ADHD, and dyslexia. Thirty-one semi-structured interviews were conducted with participants who had lived experience with these focal groups. Through thematic analysis of their narratives, the study uncovered patterns highlighting the perceived relationships between designed landscapes and sensory sensitivities in neurodivergent individuals, encompassing both heightened sensitivity (hypersensitivity) and reduced sensitivity (hyposensitivity). Emergent themes included individual and personal factors, sensory affordances, the benefits of outdoor environments, ambient environmental factors, materiality, spatial design, navigating environments, pedestrian-centric transportation, sensorimotor movement, safety, refuge, human settlement types, social environments, and accessibility plus inclusion. Subthematic patterns within these larger thematic categories were also identified. Study participants revealed significant sensory barriers and sensorially supportive elements of designed outdoor environments, along with promising design interventions. The findings unveil the advantages of designing multi-sensory landscapes tailored to atypical sensory needs, emphasizing the importance of fostering inclusion by designing landscapes that reflect the communities they serve. This concept is encapsulated in the development of the Sensory Responsive Environments Framework (SREF), the emergent theoretical framework of this study.

Keywords: sensory sensitivities; autism; ADHD; dyslexia; landscape architecture; neuro-architecture; neuro-inclusive design; sensory responsive environments

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1. Introduction

We live in an era of growing awareness of neurodiversity, which encompasses a range of profiles and identities such as autism, ADHD, and dyslexia, among others. As this list of recognized profiles and diagnoses expands, the fields of landscape architecture and urban design, as well as the built environment, are still attempting to understand how to accommodate these diverse needs [1]. Meanwhile, spatial and health inequities continue to affect these marginalized groups and present their families with persistent challenges. It is estimated that 15–20% of the global population falls under the umbrella of neurodivergence, with sensory processing sensitivities frequently affecting their experience of designed outdoor and public spaces, among other environments [2,3]. According to the World Health Organization [4]:

> "*Interventions for people with autism and other developmental disabilities need to be designed and delivered with the participation of people living with these conditions. Care needs to be accompanied by actions at community and societal levels for greater accessibility, inclusivity, and support. . . All people, including people with autism, have the right to the enjoyment of the highest attainable standard of physical and mental health*".

The overall aims of this qualitative study were to better understand the perceived experience of environmental impacts on neurodivergent individuals with sensory sensitivities and to empower those who struggle with sensory processing challenges, alienation, inequity, and invisibility to fully participate in and benefit from designed and built environments. A participatory action approach was used to both develop the research methodology and identify design interventions in outdoor environments that can create sensorially supportive and neuro-inclusive spaces through collaboration with the neurodiverse community.

The central research question was: "How do individuals with lived experience of neurodivergence, particularly those belonging to neurominority groups such as autism, ADHD, and dyslexia, perceive the relationship between designed outdoor environments and sensory sensitivities (hypo and hyper) experienced by neurodivergent individuals?" Subsequently, two sub-questions explored perceived sensorial barriers and elements that are considered sensorially supportive by these same participants: "What are the qualitative insights of individuals who have lived experience with neurominority groups, such as autism, ADHD, and dyslexia, into the perceived barriers they encounter in relation to accessing and utilizing designed outdoor environments?" and "What are the qualitative insights of individuals who have lived experience with neurominority groups, such as autism, ADHD, and dyslexia, regarding the aspects of outdoor environments that they perceive to be sensorially supportive?"

According to the United Nations [5], approximately one in every six humans suffers from some form of neurological disorder. Additionally, a study conducted by the Center for Disease Control and Prevention [6] found that during the period from 2009 to 2017, nearly 17% of children aged 3–17 years were diagnosed with developmental disabilities, including autism spectrum disorder and attention-deficit hyperactivity disorder, or learning disabilities, such as dyslexia. Further, it is estimated that approximately 10 to 15% of children are affected by sensory processing disorders [7] (also understood or referred to as sensory sensitivities rather than disorders by some). While these startling statistics call for attention, it is important to acknowledge that awareness of neurological differences has been present for some time. This recognition has paved the way for conversations around neurodiversity and sensory sensitivities, promoting understanding of the diverse ways in which individuals experience and navigate the world.

Simply put, the term "neurodivergence" signifies a divergence in one's brain and/or nervous system. In 1988, sociologist Judy Singer coined "neurodiversity", suggesting that diverse neurological conditions stem from natural human genome variations [8]. It refers to groups of individuals who, while falling under the umbrella of neurodiversity, may not necessarily have a disability or medical condition to be cured [9,10]. While neurodiversity was intended to act as a non-label, unveiling the vast potential of human experiences, this language still tends to create an "us versus them" dynamic—a binary nature—which calls for, and is likely to drive, transformative changes in our language choices. Although binary approaches are becoming increasingly challenged, strategically leveraging this existing language is key to moving beyond a uniform, or to put it another way, a monotone, thought paradigm.

Neurodivergent individuals exhibit a range of cognitive processes, learning styles, and ways of processing information, all stemming from variations in brain functioning. This diversity in neurocognition exists not merely along a spectrum, but, as Finnigan [11] suggests, more aptly resembles a prism. The multifaceted nature of neurodivergence results in a diverse array of characteristics among individuals [12], including sensorial ones. Neurominorities, as described by Walker [13], are neurodivergent individuals who share intrinsic profiles such as autism and dyslexia that shape their identities. Yet, they often encounter prejudice, misunderstanding, discrimination, and/or oppression. Further, within the framework of neurodiversity, the concept of "neurotype" and the term "neuro-atypical" have emerged, providing more language options to describe those who are wired differently. In contrast to the term "neurodivergent", the term "neurotypical" is used in the neurodiverse community for those whose neurological development aligns with societal norms [14]. While this study did not center around medical diagnoses or the quest for cures, it acknowledged and incorporated valuable insights, perspectives, and terminology from the medical community, in balance with respecting the cultural choice language of the user groups represented in this research effort.

Our senses work together to create a multi-sensory experience, providing valuable information about the external world and influencing our perceptions, emotions, and behaviors [15,16]. Research has shown that difficulty in integrating and processing environmental and sensory information is commonly observed in various neurodivergent profiles including, but not limited to, autism, ADHD, and dyslexia [7]. According to Dr. Amy Wagenfeld [17], sensory processing disorders (SPD), also known as sensory modulation disorders, can significantly affect how individuals perceive and interact with their surroundings. This includes difficulties in sensory integration, which impacts various sensory systems, such as the visual, auditory, olfactory, gustatory, tactile, proprioceptive, vestibular, and interoceptive systems [16]. Our understanding of the senses has expanded beyond the traditional five senses (refer to Figure 1) to include vestibular (movement and balance), proprioception (body position awareness), and interoception (internal bodily sensations) [7,18]. However, the notion of eight senses may not capture the entire picture. As indicated by Blakemore [19], cognitive neuroscience research suggests the existence of up to, or more than, 33 distinct senses, highlighting the ongoing potential for discovery.

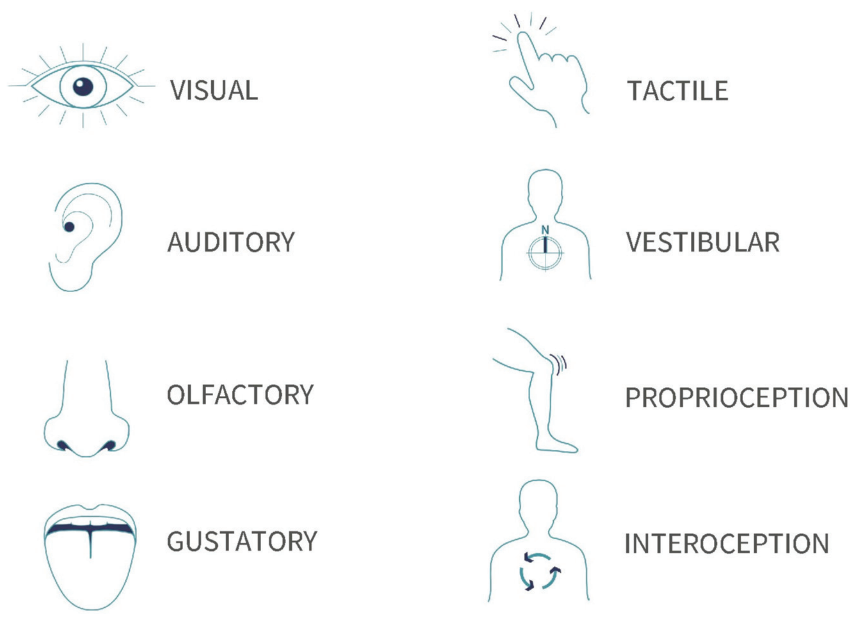

Figure 1. The eight senses. Figure created by the author.

Those with sensory sensitivities may encounter two primary sensitivity patterns: hyposensitivity (under-responsiveness) and hypersensitivity (over-responsiveness) [7,20,21]. Sensory sensitivities are known to manifest in various ways, including sensory avoidant behaviors such as an aversion to touch or smells, and sensory-seeking behaviors like self-stimming (repetitive actions that help with sensory regulation). To visualize this concept, a sensory prism graphic is presented. It illustrates the spectrum of hypo- and hyper-sensitivities across the eight sensory systems as a whole, in a non-dichotomous manner [11]. While the "average" neurotype, or typical sensory system, is symbolically represented by the dashed lines in the center of The Sensorial Prism™ (refer to Figure 2), the concept of an average neurotype is an assumption that may prove to be over-simplistic.

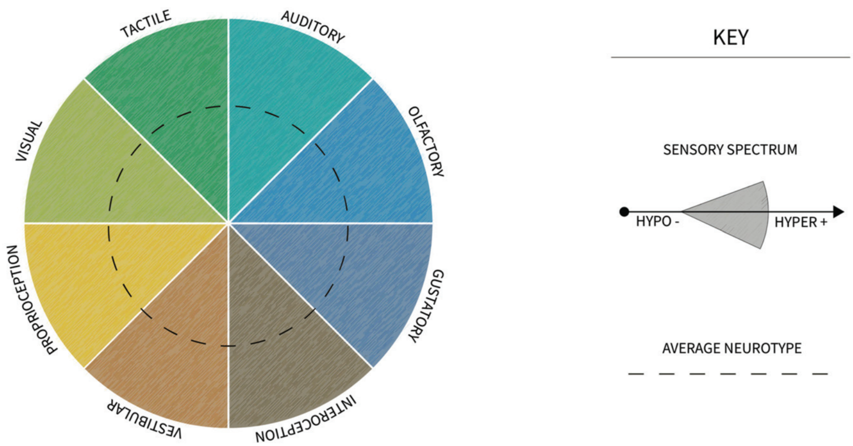

Figure 2. The Sensorial Prism™. Created by the author.

According to the current body of literature, impaired senses can lead to motor, spatial, and social challenges. Some individuals may also encounter synesthesia, where one sensory pathway triggers another [20,22]. Difficulties in processing sensory stimuli, such as colors, patterns, artificial lighting, smells, and temperatures, have been linked to increased susceptibility in environments for neurodivergent individuals. However, the acoustic environment is considered the most significant sensory element impacting user experience for those experiencing SPD and/or sensory sensitivities [23–27].

Individuals with sensory sensitivities have often expressed experiencing built environments, particularly public spaces, as uncomfortable and hostile [3,9,26,28,29]. Currently, public spaces often lack considerations for neurodivergent needs, which can contribute to social, physical, and mental health issues [30]. Further adding to this lack of consideration, the Americans with Disabilities Act addresses physical impairments, yet neglects sensory needs [26,29]. This oversight highlights a significant gap in accessibility and inclusion. According to Toronyi [27], landscape architects and urban designers have a responsibility to design inclusive spaces suited for all users, beyond the current mandates of ADA compliance: "*Landscape architects and urban designers are tasked with the critical responsibility to design inclusive and accessible environments for all users, including those with physical, sensory, developmental, or cognitive disabilities. The autistic and neurodivergent community is one of many underserved disabled communities whose needs are not addressed in ADA standards or in Universal Design*".

Although there are remaining gaps, efforts to create spaces and design guidelines addressing sensory experiences in autism have occurred, for instance, with Mostafa's The Autism ASPECTSS™ Design Index and other guidelines [26,31], as well as recommendations from Sachs [32] and Gaines [33]. These available guidelines mainly target autistic children, indoor environments, and/or specific therapeutic settings. While significant progress has been made, voids exist in understanding sensory needs and design strategies for other neurotypes and autistic adults as they navigate the public world, particularly in designed and built outdoor environments. Additionally, the scarcity of data on neurodivergent adults holds the potential to mislead us into thinking that neurodivergent individuals fade away in adulthood, or simply disappear; they do not.

More comprehensive research spanning generations is necessary to formulate inclusive strategies that address the multi-generational needs of neurodivergent individuals in built environments. This is essential as individuals navigate the demands and expectations of daily life which depend on, and are supported by, the environments we design and build. In the design of these spaces, it is imperative to consider who we are including and who we might be inadvertently excluding due to overlooked sensory sensitivities and invisible disabilities. Recognizing the ongoing debate about the multitude of human senses emphasizes the need for a continuous, adaptive effort to both seek out understanding of, and design spaces that accommodate, these diverse and inherently human experiences. By engaging with lived experiences, we can begin to chart a course toward creating environments that are more inclusive and accessible for those with invisible disabilities and sensory sensitivities.

2. Materials and Methods

Tracy [34] elucidates that qualitative research, as demonstrated through the phronetic iterative approach utilized in this study, diverges from conventional lab experiments by emphasizing deep engagement, interpretation, and the blending of theory with empirical data, all the while highlighting the importance of self-reflexivity and socio-historical contexts. Building on this theoretical backdrop, this research study explored the complex interplay between sensory sensitivities, neurodivergence, and the design of public-facing outdoor built environments.

2.1. Methodological Approach

Incorporating a diverse array of theories and methodologies, this study aimed to tackle critical issues, understand lived experiences, and provide detailed insights primarily in line with the phenomenological approach. The research methodology was also inspired by participatory action research (PAR), as it aimed to invert the traditional top-down approach to knowledge generation. Foucault's quote, as cited in [34], resonates with this focus: *"When knowledge, education, and credentialing are only available to dominant, powerful, and wealthy people, the knowledge of subordinate members—which may be crucial for understating a research problem—is often hidden, ignored, or undermined"*.

To gain a comprehensive and nuanced understanding of cultural phenomena from the perspective of those within the culture being explored, this study also adopted an inductive emic approach, meaning it focused on understanding from the insiders' viewpoint. This involved immersing into the culture to provide thorough insights into cultural circumstances, delving into polyvocality, exploring the political complexities of public land and shared spaces, examining broader societal issues of equity, diversity, and inclusion, and critiquing the originating power structures. Building on this, the research approach intentionally moved beyond the confines of diagnoses, peeling away the reductive lens. Instead, it focused on the user experience of individuals with sensory sensitivities, emphasizing engagement with the lived experiences and perspectives of study participants rather than predetermined criteria and constraints.

Through a review of the literature, insights into the current and adjacent design recommendations in the field, the neurodiversity movement, contemporary disability models, medical understanding, relevant historical background, and associated theories were recognized as sensitizing concepts. Identified early in the research process, these concepts served as a foundational starting point and were instrumental in guiding a cross-analysis with the study's findings. Alongside the literature review, input from members of the neurodiverse community further enriched the understanding of key issues and the shaping of the research framework, which was instrumental in developing interview protocols that effectively engaged study participants.

With its phenomenological focus, the IRB-certified portion of this qualitative research employed a semi-structured interview protocol. Open-ended questions allowed participants to freely express their thoughts, capturing the rich and varied aspects of their lived experiences (the interview protocol is available in the Supplementary Material). It delved into the complexities of their identities and sensory experiences in relation to designed and built outdoor environments, specifically probing sensory discomfort, sensory support, and environmental impacts. Additionally, including questions about participants' suggestions for improving outdoor spaces and their advice for designers reflects the participatory and action-oriented aspect of this study, generating insights and recommendations for practical applications and providing a preliminary roadmap for transformative change.

2.2. Participant Data and Sampling

Purposive sampling techniques, including maximum variation and snowball sampling, were utilized to select participants with lived experience with autism, ADHD, and dyslexia. To ensure a comprehensive understanding of the neurodivergent experience, the study included participants with secondary and professional lived experiences, in addition to those with firsthand lived experiences, to account for individuals unable to provide informed consent to participate themselves as required by IRB requirements. This study adhered to ethical research standards and received IRB certification (COMIRB number: 22-2175).

Given the complexity of the subject matter, which encompassed overlapping identities, diagnoses, experiences, and perspectives, data saturation was achieved with a robust participant cohort of thirty-one, ensuring the study's rigor. For instance, many with professional ("P") experience supporting members of the neurodiverse community also had firsthand ("F") and/or secondhand ("S") familial experience with neurodivergence and sensory sensitivities. To address this complexity, personal identifiers, such as "SF", were used to align the interviewee's perspective with the discussion. For clarity, the first introduction of a participant's pseudonym in a section will include a quotation with their identifier, providing context for readers to understand the perspectives they represent. For example, a professional experience with reference number may present as "P1".

Direct quotes were extracted from interviews to comprehensively portray the perceived relationships of lived sensory experiences in outdoor environments. While many participants commented on specific themes, only a few quotes were selected to illustrate emergent themes and highlight participant narratives in the thematic narrative analysis. Minor spelling and grammar edits were made to enhance readability while preserving participants' voices and content. Respect and acknowledgment for individual identity preferences is reflected in the participant data table and thematic narrative analysis, which includes preferred pronouns (e.g., She/They), preferred pseudonym if expressed (otherwise, one was assigned), and preferences for either person-first or identity-first language.

Participant recruitment (see Table 1) involved community organizations supporting neurodiverse communities, academic networks, professional networks, and personal networks. Half of the participants were from Colorado, while others were associated with six additional states in the USA (New Mexico, Ohio, Texas, Iowa, California, New York, and Washington). Diligent efforts were made to ensure equitable representation across various recruitment sources.

Table 1. Participant data.

Identifier	Pseudonym	Diagnoses/Identity/Lived Experience	Pronouns	Age	Interview Type
P1	Manni	Clients: Autistic Adults	He/Him	35–50	Face to Face
F2	Rose	Self: ADHD + Dyslexic	She/They	18–34	Synchronous mediated
F3	Ashley	Self: Autistic + ADHD	She/Her	18–34	Asynchronous mediated
P4	Devin	Clients: Autistic	She/Her	35–50	Synchronous mediated
F5	Craig	Self: ADHD + Dyslexia	He/Him	18–34	Face to Face
F6	Doe	Self: Dyslexic, ADHD/ADD, + Other Neurodivergences	He/Him	18–34	Face to Face
FS7	Magnolia	Self: Autistic | Young Child: Autistic	She/Her	18–34	Synchronous mediated
F8	Kira	Self: ADHD + Dyslexia	She/Her	35–50	Synchronous mediated
F9	Elijah	Self: Autistic, ADHD/ADD, + OCD	He/Him	18–34	Synchronous mediated
S10	Ruby	Her Young Child: Autism (1) + ADHD Combined Type (11) | Partner: ADHD	She/Her	35–50	Synchronous mediated
S11	Kevin	His Young Child: Dyslexic + Severe ADHD	He/Him	35–50	Synchronous mediated

Table 1. *Cont.*

Identifier	Pseudonym	Diagnoses/Identity/Lived Experience	Pronouns	Age	Interview Type
S12	Angelina	Her Young Child: Autistic	She/Her	35–50	Synchronous mediated
FS13	Summer	Self: ADHD + Autistic	She/Her	18–34	Synchronous mediated
F14	Brooke	Self: Dyslexic + ADHD	She/Her	35–50	Synchronous mediated
FPS15	Lily	Self: ADHD + Coordination Disorder | Clients: Autistic Children | Adult Sibling: Autistic	She/Her	18–34	Synchronous mediated
S16	Rachel	Her Adult Sibling: Asperger's Syndrome	She/Her	18–34	Synchronous mediated
PF17	Gabriel	Self: Neurodivergent | Clients: Autistic, ADHD, Down syndrome, TBI + PTSD (Adults)	He/They	35–50	Synchronous mediated
F18	Carlisle	Self: ADHD	She/Her	18–34	Synchronous mediated
P19	Rupal	Clients: Autistic Children	She/Her	65+	Synchronous mediated
FS20	DeeJay	Self: Autistic + ADHD | Adult Sibling: Dyslexic	She/They	50–64	Synchronous mediated
F21	Damien	Self: Asperger's Syndrome	He/Him	35–50	Face to Face
S22	Big Casey	His Multiple Adult Children: Autistic, ADHD, Turners Syndrome, Dyslexic + Other Neurodivergences	He/Him	65+	Face to Face
F23	Gigi	Self: ADHD/ADD + Other Neurodivergence	He/Him	35–50	Face to Face
F24	Rain	Self: Dyslexia, Dyscalculia, + ADD	She/Her	35–50	Face to Face
PS25	Susan	Her Adult Children: Autism, ADHD + OCD	She/Her	50–64	Face to Face
PS26	Raya	Clients: Neurodivergent, Autistic, + SPD | Family: Trauma-Related Neurodivergence	She/Her	50–64	Face to Face
SF27	Tulip	Self: Neurodivergent | Adult Children: ADHD + Autism | Mother: Photosensitivity + Seizures	She/Her	50–64	Face to Face
S28	Hannah	Her Adult Child: Autistic	She/Her	50–64	Synchronous mediated
F29	Brandon	Self: Autistic, Depression, Anxiety, OCD, + BPD	They/Them	18–34	Synchronous mediated
PFS30	Willa	Clients: Adults + Children with Autism | Niece: Sensory Challenges | Self: ADHD	She/Her	18–34	Face to Face
SP31	Bob	Clients: Autistic | Adult Child: Autistic	He/Him	50–64	Synchronous mediated

F = Firsthand Lived Experience, S = Secondhand Lived Experience, P = Professional Lived Experience.

2.3. Analysis Process

Informed by phenomenology, this study utilized a qualitative approach for analysis. Thematic narrative analysis was employed to delve into the stories and experiences shared by participants, allowing themes to emerge during interview transcription. This approach aligned with the phenomenological principle of letting the data speak for itself, aiming to capture the underlying structures and meanings of participants' subjective experiences.

Primary and secondary coding were conducted, followed by a negative case analysis to explore instances or perspectives contradicting emerging themes. The analysis process was iterative, involving cycles of reflection, revisiting the data, literature, and refining interpretations. While also integrating elements of triangulation to ensure methodological rigor, a crystallizing approach was adopted to embrace the complexity and multiplicity of insights.

Elements of Triangulation in the Study:

- Semi-structured Interviews: Interviews with participants from different perspectives captured a range of lived experiences related to neurodivergence and sensory sensitivities.
- Member Checks: Engaging with participants at numerous stages helped to ensure findings were representative.
- Peer Reviews from an Interdisciplinary Thesis Committee: Scrutiny by experts from different disciplines added validation and reduced disciplinary biases. The research greatly benefited from the contributions of the thesis committee:
    - Dr. Temple Grandin (Colorado State University) provided insights into sensory processing challenges and autism, informing the study's conceptual framework.
    - Dr. Soumia Barhan (University of Colorado) contributed her expertise in qualitative research methodologies and intercultural rhetoric, enhancing research protocols and analysis.
    - Dr. Jody Beck (University of Colorado) offered perspectives relevant to the fields of landscape architecture and urban design, along with his expertise on the interplay between politics and landscapes.
    - Associate Professor Joern Langhorst (University of Colorado) was pivotal in the initial development of the study, including a preliminary independent ethnographic study, and securing IRB Certification to ensure ethical standards.
    - Dr. Amy Wagenfeld (University of Washington), as an occupational therapist and design consultant, served as thesis reader, bolstering the study's interdisciplinary applicability.

Elements of Crystallization in the Study:

- Literature Review with Theoretical Frameworks: In the context of crystallization, using the literature to establish a theoretical framework helped to integrate and compare the study's findings with broader theoretical contexts, enriching the interpretation.
- Self-Reflexivity and Auto-Ethnographic Insights: The incorporation of the researcher's self-reflexivity, detailing potential biases and assumptions, along with an auto-ethnographical report of their personal history with neurodiversity, sensory sensitivities, and independent ethnographic work within an autistic and neurodiverse community, enriched the research process. This is available in the introduction section of the full study [11].

3. Findings

The findings of this qualitative research captured lived sensory experiences in outdoor settings for members of the neurodiverse community, revealing emergent themes across various perspectives, diagnoses, and identities, and offering insights into the nature of atypical sensory experiences in outdoor settings. While the insights are not based on quantifiable measures, the contributions made by participants to specific emergent themes are acknowledged. To assist readers in understanding the qualitative data, emergent themes are presented in Table 2. Each theme is accompanied by a symbol (≥) denoting the number of study participants associated with each in intervals of five, representing the theme's strength, which often exceeds the minimum prescribed requisite of three participants to discern a thematic pattern.

Table 2. Emergent themes: experience of outdoor environments.

Category	Emergent Theme	Participant #'S
Sensory Profiles	Individual + Personal	≥30
	Sensory Affordances	≥20

Table 2. *Cont.*

Category	Emergent Theme	Participant #'S
Environmental + Site Factors	Benefits of Outdoor Environments	≥25
	Ambient Environmental Factors	≥30
	Materiality	≥15
	Spatial Design	≥25
	Navigating Environments	≥20
	Pedestrian-Centric Transportation	≥25
	Sensorimotor Movement	≥20
	Safety	≥20
	Refuge	≥20
Societal Factors	Human Settlement Types	≥15
	Social Environments	≥20
	Accessibility + Inclusion	≥25

3.1. Thematic Narrative Analysis

Many landscapes are purposefully designed, modified, and constructed for human use across various settlement types, such as urban, suburban, and rural areas. They serve a range of purposes, including recreation, social gathering, play, health and wellness, transportation, and commercial activities, among other functions. The designed and built outdoor environments relevant to this study include, but are not limited to, parks, plazas, event spaces, streetscapes, transportation systems, educational settings, workplaces, and commercial environments. Meaningful access to these landscapes significantly impacts individuals' overall quality of life, well-being, and societal participation, while also influencing social interactions, health equity, and economic opportunities. The research findings revealed a thick description of neuro-atypical sensory experiences in outdoor built environments, emphasizing the relevance of understanding and accommodating unique sensory needs in the planning and design of these human environments.

3.1.1. Individual and Personal Factors

The sensory themes and perspectives in the narratives of individuals with lived experience in neurodivergence (specifically autism, ADHD, and dyslexia) encompassed hyposensitivities (reduced sensitivity and/or sensory-seeking behaviors) and hypersensitivities (heightened sensitivity and/or sensory-avoiding behaviors). These sensitivities spanned various sensory modalities as they related to designed environments. Among the participants, roughly half reported lived experiences with hyposensitivities, while the larger majority expressed experiences with hypersensitivities, with many reporting both hypo- and hyper-sensitivities. These experiences, which included sensory stacking, collectively encompassed all eight sensory systems represented in this study. They were expressed by individuals with various diagnoses, neurodivergent identities, and perspectives, including firsthand, secondhand, and professional experiences.

While many participants mentioned difficulties with spatial awareness, balance, and the need for sensorimotor movement, specific terminology to describe experiences with proprioception, vestibular, and interoception were not readily accessible for most study participants. For ease of understanding, these sensory systems were collectively referred to as "body senses" rather than "foundational senses" during interviews. This is a term that, while not officially recognized in neuroscience or occupational therapy, helped facilitate more accessible discussion about these foundational sensory experiences for study participants.

Participants approached discussions of their sensory experiences in varied ways. For instance, some explicitly described their sensory experiences with fluidity at the interview's outset, while others framed their sensory challenges within environmental contexts, such as being challenged by traffic noise. Some noted that they viewed their sensory experiences as "normal" at one point in their lives, only later realizing they had unique sensitivities. The diverse range of sensory experiences within ADHD, dyslexic, and autistic profiles emphasized the importance of recognizing individual differences and adopting flexible, varied approaches to understanding and designing responses. Moreover, many—particularly women—expressed missed or misdiagnoses. Some study participants also linked past traumas to their sensory perceptions.

For many participants, their semi-structured interview became an opportunity for self-discovery and reflection. By taking the individual and personal factors into consideration, the groundwork was set for interpreting the following findings with an open and empathetic approach.

3.1.2. Sensory Affordances

The majority of participants emphasized the role of sensory affordances—features that can either support or hinder sensory experiences—in designing supportive spaces for neurodivergent individuals. Designing for sensory affordances in outdoor built environments involves going beyond the classic five senses to include proprioception, vestibular, and interoception, focusing on addressing sensory overwhelm and underwhelm, minimizing accessibility barriers, and acknowledging the impact of inherently multi-sensory environments.

Both sensorially distressing and sensorially supportive environments were noted to impact the well-being of the neurodiverse community in various outdoor settings like active transportation systems, streetscapes, parks, commercial settings, and academic environments. Most study participants pointed out the absence of designed landscapes tailored to meet neurodivergent needs across various geographic regions in the United States, highlighting that existing outdoor built environments fail to address their sensory requirements and are inadequate in sensory affordances. This oversight was often expressed as being tied to a sense of isolation and limited opportunities for neurodivergent individuals due to sensory barriers including certain smells, bright lights, visual overwhelm, excessive noise, and poor sensorimotor engagement opportunities.

Moving on to specific examples, Raya (PS26), an occupational therapist, among other expertise, discussed her experience in finding outdoor environments designed with sensory impairments in mind in her coastal city. She expressed, *"They're very, very hard to find. I will visit, you know, play spaces that are 'universally designed' shall we say? And I can't figure it out. I can't, I think no, you've missed the mark. You've missed the mark. You've missed the mark"*. She shared her perspective on the design of sensory gardens, stating, *"Like, no, you're only very cursorily hitting the five basic senses. You're not considering proprioception, not considering the vestibular sense. You're not considering interoception"*. She went on to explain that her city attempts to consider designing sensorially supportive spaces, but that there are shortcomings: *"It's a lack of understanding... Many of the spaces just don't provide sensory affordances. And just because it's a new and novel thing..."* She proceeded to clarify that *"it's not new and it's not novel, it's just not understood"*.

DeeJay (FS20) added to this sentiment, expressing, *"There's just so many [spaces] that are not accommodating. It's endless... The exception is the spaces that are"*. DeeJay shared their search for a trail catering to neurodiverse sensory needs. They explained, *"I have a friend, he's a landscape architect. He's telling me about it... it's a neurological trail, and it's not up here... I've been looking for it"*. Their quest for a neuro-inclusive trail that offers sensory affordances in the Pacific Northwest resembled the metaphorical search for the Holy Grail. Importantly, this search signified an achievable aim and the potential to create inclusive public spaces that cater to these unique, yet innately human, sensory needs.

The preceding quotes represent a small sample of narratives collected from more than 20 study participants, directly focusing on the challenges neurodivergent individuals and neurodiverse families face regarding limited sensory affordances in designed environments, emphasizing the absence of landscapes catering to their needs.

3.1.3. Human Settlement Types

The study involved participants from rural, suburban, and urban areas, focusing on the distinct perceived challenges and preferences of each, especially regarding sensory attributes and population density. It emphasized that different settlement types present particular challenges for neurodivergent individuals in domains such as designed outdoor environments, support services, transportation, safety, housing, and medical care, which were often communicated as not fully addressing their needs and limiting their options and opportunities. The next section will explore how environmental factors influence the experience of neurodivergent individuals with sensory sensitivities and sensory processing challenges.

3.1.4. Benefits of Outdoor Environments

Investigating the intricate connection between neurodivergent individuals and their sensory experiences, this qualitative study provided insights into the potential therapeutic effects and sensory comfort that outdoor spaces, especially natural environments with lighter anthropogenic intervention, can offer. Building on this understanding, many participants reported experiencing sensory distress in public-facing indoor environments, and found outdoor settings to generally be more supportive of their sensory needs.

For instance, Susan (PS25) described indoor spaces as sensory nightmares: "*So many indoor spaces are sensory nightmares, with bright lights and loud sounds... For instance, when I go to Safeway, the temperature feels like 40 degrees, and the music is way too loud and awful... The whole experience is a sensory nightmare*". In addition to shopping facilities, numerous participants expressed sensory-related challenges in many other public indoor settings, including K-12 schools, workplaces, studios, and academic venues, and discussed the detrimental effects of enduring prolonged sensory distress. This suggests an opportunity to leverage landscapes and natural settings to help alleviate sensory distress for individuals with atypical sensory systems experiencing sensory overload from overstimulating indoor environments, such as shopping centers.

As participants discussed sensorially supportive aspects of outdoor environments, a pattern emerged for preference of natural settings such as forests, gardens, nature parks, and trails. For instance, Gabriel (PF17) shared, *"Nature is incredibly therapeutic and usually advantageous. On the positive side of things, I've taken clients to gardens and witnessed a palpable effect on both them and ourselves... Tranquility and peace".* Gabriel also emphasized the importance of natural lighting and incorporating plants as much as possible.

Further, several participants alluded to a spiritual connection from their time spent in nature, like DeeJay (FS20), who shared their sense of elation: "*I have intense sensory encounters with nature, particularly through visuals. I feel a synesthetic connection with my vestibular system, where I almost feel suspended in a moment that can last for what seems like a long time. It's not all bad [in reference to sensory sensitivities]... I love going outside in nature and moving around, whether it's dancing or engaging in free-form movement".*

Interview participants lauded nature's therapeutic and calming effects on sensory well-being, highlighting the supportive roles of biological and geological elements such as greenery, biodiversity, and natural water bodies over anthropogenic elements. Reflecting this, Elijah (F9) described his ideal sensory-supportive space: *"I would love to see biodiversity, orchids, and trees. I also enjoy the presence of interesting caterpillars because animals keep me calm. Additionally, bird sounds, especially in the morning, help me find peace".*

There was also an indication that incorporating natural patterns could be beneficial. Big Casey (S22) shared: "*One of my autistic kids cannot step on cracks and sidewalks. They confided in me, and I explained that I had the same problem when I was younger. In the city, there may be too many regular and repetitive patterns, which can be overwhelming. In trails and open spaces like this, there are no linear regulated steps that you have to step over; you're just in nature. So, urban areas may feel too repetitive, concrete, and artificial*".

Gigi (F23) also explicitly favored landscape design that follows natural patterns and contours: "*It's more pleasant when it follows contours of the land... In gradual curves and shapes* *and to sort of follow contours... not necessarily hide it in the environment but take its cues from the environment*".

While outdoor natural spaces, particularly those with abundant wildlife, lush vegetation, water, and unaltered geological features, were described as sensorially supportive by the majority of study participants, many also pointed out various difficulties related to the certain unappealing sensory aspects of such environments, like encounters with flying and stinging insects and the tactile sensation of dirt or plants.

3.1.5. Ambient Environmental Factors

The qualitative insights of this study presented connections between ambient environmental factors, including noise pollution, artificial lighting, atmospheric conditions, and environmental scents, and their influence on the sensory well-being of neurodivergent individuals. Notably, noise pollution emerged as a leading contributor to sensory distress in outdoor environments, with traffic-related noise, crowds, and echoes being particularly disruptive.

For instance, Kira (F8) shared the impact of noise on her well-being: "... *traffic is a huge thing for me... Really loud, sudden noises which tend to happen when you're near busy traffic centers*". She expressed her challenges in urban environments: "*I struggle with those types of environments... Even at city parks, it's not relaxing, it's not enjoyable. There's still too much movement. I can still hear all the city sounds, all that kind of thing*". The findings demonstrated that noise from human-made sources, such as loud music on trails, noisy playgrounds, industrial sounds, shouting people, crowds, repetitive sounds like lawn mowers, and sudden loud noises (like school bells), can impede neurodivergent individuals from fully accessing or enjoying places and activities. Participants expressed favor towards anthropogenically quiet settings, like trails and parks where biophonic and geophonic sounds, like moving water and bird song, provide a serene escape from urban noise.

Many participants found artificial lighting overwhelming and preferred natural lighting, highlighting the need for lighting improvements in outdoor environments that consider factors such as temperature, brightness, flickering, placement, and access to natural light to reduce visual sensory barriers. For instance, Ruby (S10) shared her experiences and observations regarding her neurodivergent child's sensitivity to light: *"Places where there's a lot of really artificial light, temperature-wise, are not preferred. He prefers both a warmer temperature and lower voltage".* Ruby noted that bright blue light (4000 K+) can be overwhelming and described how natural light is more beneficial for her child's well-being, stating, *"Natural sunlight makes a big difference for him... I notice a substantial difference in mood".* Adding to this, numerous participants raised concerns regarding their sensitivity to flickering lights and flashing stimuli like Brooke (F14) who shared, *"100% flickering of lights, that is just like, oh, nothing gets me worse".*

Several study participants expressed heightened sensitivity to various scents, such as synthetic fragrances, body odors, and food, with the majority expressing favor for natural scents related to plants and flowers. For instance, Damien (F21) found solace in the scent of a tree on a college campus, which provided a comforting presence in an otherwise unwelcoming environment: *"They had a park in my community college... Well, it was actually just a bench under a really big tree. And I would sit down at the park bench, even in times when I felt like I wasn't really welcome at school. I'd just close my eyes and take a nap. The tree was in the sun but provided a little bit of shade. It looked like one of those Japanese trees, like sometimes [that] would have cherry blossoms—a flowering tree. It had a scent of cinnamon and peppermint, and it created a really peaceful atmosphere... gave off a nice scent that was comforting".* Earlier in the interview, he highlighted the significance of the cinnamon scent as part of his envisioned ideal sensorially supportive place. This observation suggested a connection between place, scent, memory, and a feeling of welcoming and inclusion.

While scents from nature were often expressed as comforting and inviting, there were those who expressed sensitivity and aversion to anthro-odors like cigarette smoke, trash, perfumes, and body odors. For example, Tulip (SF27) shared her neurodivergent son's struggles with olfactory hypersensitivity: *"Anytime we went to the grocery store, I would* *end up having to leave the grocery store and lose the groceries there and take them [referring to her children] home. We could not get through the grocery store... It was the smells, the smells of the people...*"

Atmospheric conditions, like temperature and air circulation, and allergens, like pollen, dust, mildew, and wildfire smoke, were also observed to impact sensory comfort for those with sensory sensitivities. Some participants shared that they were sensitive to extreme temperatures, with both heat and cold prone to trigger sensory overwhelm; a couple of participants attributed this to delayed temperature sensitivity.

In summary, the qualitative insights gained from this study emphasized the potential effects—both detrimental and beneficial—of ambient environmental factors within designed environments on the overall sensory experiences of the neurodiverse community members represented in this study. The findings also highlighted that discerning anthro-stimuli (originating from human activities) from bio-stimuli (originating from biological sources other than humans) and geo-stimuli (stimuli that are geophysical) for ambient environmental factors may be key in distinguishing sensory-friendly and sensory-hostile environments from one another for the neurodiverse community. Design strategies recommended by participants to enhance sensory comfort included utilizing ambient buffers, thoughtfully selecting and placing materials (including living materials), consciousness in site selection, and strategic spatial layout.

3.1.6. Materiality

This study revealed that the selection of materials in design can play an impactful role in accommodating the unique sensory requirements of neurodivergent individuals. A noteworthy inclination for natural materials emerged, with discomfort noted in artificial environments lacking material authenticity, a concept introduced in this study. Participants also expressed strong preferences for stable walking surface materiality and muted colors in landscape design.

"Material authenticity" refers to the use of natural materials—such as wood, stone, and natural fibers—alongside other elemental features in the design and construction of environments, over synthetic or artificial alternatives. This concept aims to create sensory-friendly environments that not only enhance user experience but also foster a connection with the natural world. Such environments were perceived as soothing and stabilizing for individuals with atypical sensory systems. Conversely, environments that lack material authenticity, opting for synthetic or highly processed materials, were perceived as less inviting and even discomforting to these same individuals, as suggested by the research findings. Specifically, chrome emerged as a visually disconcerting material in several interviews, described as cold, uncomfortable, and devoid of emotional appeal. For instance, Gigi (F23) shared that *"chrome is the worst offender"*.

Damien (F21) highlighted how artificial environments exacerbate his feelings of isolation, emphasizing the need for genuinely inclusive designs that resonate on a natural level. He stated, "*you want to make something really inclusive, yet they feel natural. Because autistic people, people who aren't normal, people who are deaf, people [who] are blind, they can tell. There's something in the gut that there's just [something] off about it, whether it's like, some postmodern art or structure...*" He further emphasized the importance of making things feel real and holistic, while acknowledging the chaotic nature of human experience, saying, *"The human experience is just kind of chaotic... You have to run towards that kind of chaos and just embrace it, and smile at it"*.

Building on this understanding, the findings indicated the potential for materiality to provide a sense of grounding and comfort for neurodivergent individuals. Doe (F6) offered an illustration of this concept, stating, *"If I'm walking outside, I experience material in different ways. For example, a building made of stone, but with a certain color, shade, and materiality, like a wood floor... I could feel it. If I don't feel anything, I feel like I'm floating. I have to feel something to know where I am"*. Doe added, *"And a lot of texture... I want something textured, feeling, and* *something that tells me I can interact"*. Doe's perspective shed unique light on how sensory feedback from materials can establish a sense of grounding, orientation, and place.

3.1.7. Spatial Design

The research findings suggest the importance of accommodating diverse sensory needs through careful site layout of public-facing environments. Emergent themes included the perceived value of providing a variety of sensory opportunities in distinct areas and achieving a strategic balance between open and enclosed spaces.

In a similar vein to openness and enclosure, the concept of proxemics—especially concerning personal space and sensory overload in social contexts—was frequently discussed. Interestingly, it was often brought up in the context of excessive activity, prompting the combined discussion of both proxemics and dynamic elements. Some participants expressed their exhaustion with focusing on specific objects or environments with excessive movement like busy roadways, while others shared that visual discomfort arises from lots of movement when combined with abundant colors, noise, or crowds of people, creating a layered sensory challenge.

The need to establish distinct zones tailored for unique spatio-sensorial needs that accommodate individual autonomy and preferences in both group and individual scenarios was particularly emphasized. For example, Kevin (S11) shared that it is essential to *"encourage variety in spaces"* and ensure there is *"enough mirroring variety in those types of spaces"*. Angelina (S12) echoed this sentiment, saying, *"Maybe having just different areas where there's a group type setting versus more individual... Just different areas"*.

3.1.8. Navigating Environments

The qualitative data revealed significant challenges that neurodivergent individuals experience in navigating built outdoor environments, particularly disorienting ones such as transportation systems, zoos, and busy markets. Additionally, the data highlighted difficulties in transitioning between different environments or activities. These narratives also underscored the need for further research into solar-based navigation and improved wayfinding design strategies.

Study participants proposed design interventions, such as creating visually accessible and clear wayfinding systems. This includes using directional cues, explicit maps, marked pathways, and consistent colors and icons to minimize confusion and support neuro-atypical navigation. These interventions aim to ease movement through space and reduce wayfinding anxiety.

Additionally, participants emphasized the importance of predictability in environments and safety considerations, such as ensuring uniform step depths in stairs and ramps. This was noted as being essential for individuals with visual sensory challenges like depth perception. Further, several participants emphasized the importance of supportive furnishings such as ergonomic, smooth-edged benches, along with ample space and proxemics in restful zones to accommodate unique sensory needs.

A surprising insight emerged from this study, as several participants reported challenges in environments where sunlight was blocked by enclosed spaces, tall buildings, and dense forests. For instance, DeeJay (FS20) described the difficulty of relying on faulty technology for navigation, especially in dense forests where the sun's position is obscured: "*I've got a cell phone with a dying battery... I can't rely on technology to lead me back... I get very disoriented in spaces, especially when you can't see where the sun is"*. Similarly, Tulip (SF27) shared her reliance on this type of natural cue for orientation, which becomes problematic in urban settings: *"I have a very good gyroscope"*, she said, *"but tall cities with tall buildings block out the sun and disrupt my directional compass"*.

3.1.9. Pedestrian-Centric Transportation Systems

The importance of landscape and urban designers recognizing and addressing the unique needs of neurodiverse user groups within transportation systems, with a specific emphasis on considerations related to pedestrians, was highlighted. While this focus closely aligns with discussions about navigating environments, the conversations extended beyond navigation, encompassing a broader perspective that included both pedestrian-centric and vehicle-centric considerations, as well as multi-modal transit.

Participants discussed challenges that urban environments with heavy traffic present, noting the negative impacts of constant vehicle noise and movement on relaxation and enjoyment of public-facing spaces. Many expressed a desire for more greenery and fewer disturbances from busy roads. Issues with multi-modal transit, like confusing layouts and the lack of green spaces at transit stations, were also noted as impacting sensory comfort. Insights were shared on designing sensory-responsive active transportation environments, emphasizing wide and well-designed pathways, with safety and visibility in mind, to mitigate sensory overload. Participants suggested restful areas with seating away from busy areas to meet diverse sensory needs, tying back to discussions on personal space.

While numerous participants voiced transportation concerns and issues, Lily's interview (FPS15) particularly encapsulated this collective sentiment: *"There are a lot more neurodivergent people walking around in your cities then you realize [in reference to city planners and designers]... and be mindful that neurodivergent people also need your spaces... they need those resources, they need the parks, the nature, the secluded areas, and may need to be able to get around in cities in ways that don't involve getting in the car. Not everyone who is neurodivergent can drive, for whatever reason they have. Just realize, they need those environments to be supportive... so have that in the forefront of your mind when developing these places, that it can really impact the experience of neurodivergent people in your city. And that can also impact their ability to work, function, and contribute... to give back. And when it's more accessible and supportive, they're going to be enabled to give back to the community".*

3.1.10. Sensorimotor Movement

Many participants found that those with atypical sensory systems derive significant value from sensorimotor movement, encompassing both enjoyment of, and a need for, this type of movement and engagement. Activities like climbing, running, swinging, and engaging in vestibular and proprioceptive input were described as calming and vital for the sensory well-being of individuals across neurodivergent diagnoses and identities. It is worth noting that multiple participants explicitly endorsed "movement as a coping mechanism", underscoring its importance as a regulatory mechanism.

Participants emphasized the necessity for multi-generational play opportunities, for neurodivergent teenagers and adults to engage in sensorimotor recreational activities without facing stigma or legal concerns. Hannah (S28) shed unique light on the safety challenges with playgrounds that impose restrictions on her adult autistic son who, while occupying an adult body, still likes to play: *"There's a lot of parents that are still afraid of neurodivergent people and they've actually talked about calling cops... It makes it dangerous for my son".* Despite her son's gentle nature, Hannah acknowledged the apprehension due to his physical stature, mentioning, *"He's big. He's 5′11″ and parents are always afraid... but he's never hurt a child".* She further shared that many play areas are tight, restrictive, and unwelcoming: *"Some of the things are too small for him to use, but he'd like to".*

The study insights suggested the advantages of incorporating play and sensory engagement features, such as multi-generational swings and recreational equipment, into parks and playgrounds for neurodivergent adults while also providing a sense of safety for the parents of small children, for instance, by having separate age-specific areas. Overall, the qualitative accounts shed light on the potential benefits of providing opportunities for movement and multi-generational parks that cater to all ages, sizes, and neuro-abilities for the inclusion of the neurodiverse community in these spaces.

3.1.11. Safety

While exploring the needs of the neurodiverse community, emphasis was placed on crafting safe landscapes and urban environments. Various issues regarding pathways, including clutter, holes, inconsistent steps, and poor drainage, were highlighted, indicating the need for safety measures to address visual hyposensitivity and prevent falls. Similarly, safe active transportation was found to require thoughtful design, through initiatives such as wider pathways and optimal visibility. Streets with heavy vehicle traffic were identified as sources of anxiety for neurodivergent individuals, especially where there is a lack of physical separation between sidewalks and roads, prompting considerations for careful site planning, sensory buffers, and visual barriers.

Clearly defined perimeters were found to be essential to prevent individuals from wandering into potentially dangerous areas, such as busy streets, large bodies of water, and wilderness, without clear paths. The concept of boundaries emerged as a significant issue, with the need to ensure a sense of safety and foster autonomy without constant supervision, as highlighted by caregivers for autistic children and adults. Additionally, physical buffers like thick vegetation were noted to enhance freedom, autonomy, and security within environments with potential hazards.

Importance was not only found in an objectively safe environment, but also in a subjective "sense of safety". For instance, Damien (F21) shared a distinctive personal experience, recounting a childhood visit to an amusement park where sensory triggers created a sense of unsafety: *"It was also like a sensory thing, but when I saw this creature, it was like something in my head would activate, well, we make this weird 'EEEEEEEE'... due to not knowing what's going to happen... It was really scary to me... Reptiles that want to eat you"*.

Building on the notion of ensuring both objective safety and a subjective "sense of safety" as integral components of creating neuro-inclusive and sensorially supportive environments, Bob (SP31) highlighted a shared sentiment among study participants: *"People need safe spaces... Why aren't we doing that for the crew... It's been scientifically proven that they really do need a place that's really built for them"*.

3.1.12. Refuge

As the interviews collectively unfolded, it became clear that there was a call for refuges in public environments. These should minimize overwhelming stimuli and offer opportunities for individuals to self-regulate before they re-engage with their surroundings, addressing the issue of sensory overload.

Susan's (SP25) narrative pressed the recognition of this significant void for addressing dysregulated moments: "*I've had this experience with my eldest all the time, and when they were very young, I didn't know what was going on. They would have complete meltdowns in stores. But in those kinds of spaces, whether you're a child or an adult, where do you go to regroup if you feel dysregulated? Where can you go? Because this is a common theme among neurodivergent people, as they become dysregulated more easily... You could go sit by the fountain, but it's in a public space with many people around you... You could go to Starbucks, but then what?... Sit in the restroom? There aren't really any intentional spaces*".

Tulip (SF27) recounted a firsthand experience illustrating the challenge of stimuli stacking, "*It was a couple hours ago... I became so overstimulated in a restaurant that I started to shut down, started to feel really sleepy, and just wanted to go home and go to bed. For me, it was the combination of both auditory and visual, it was just too much for me*". She added how directing her focus on something else in the room to manage the stacked sensory overload, consistent with what the Kaplans refer to as "soft fascinators", helped her self-regulate: "*Having plant life... Even though this was actually fake plant life, it still worked because there was enough greenery. I think plant life really helps*".

In summary, participants frequently articulated that neurodivergent individuals face significant challenges in overstimulating environments, especially those devoid of refuges from sensory stressors induced by human activity. They recommended the creation of nature-inspired spaces for solace. These should include features such as soft focal points, secluded areas, greenery, natural materials, and water. Such elements enhance self-regulation and provide the necessary sensory support that enables sensorially sensitive individuals to reset and then re-engage more effectively. The integration of sensory and social refuges into existing, overstimulating environments, without requiring major infrastructure changes, emerged as a viable strategy to enable neuro-inclusive access to public-facing and sensory-intense built environments.

3.1.13. Social Environments

Expanding on the need for social refuge, the findings from this study unearthed numerous challenges that neurodivergent individuals encounter in social environments like commercial settings, event spaces, academic settings, and workplaces. These observations warrant a dedicated section within the broader context of societal factors. The emergent patterns and ensuing subthemes are intricately linked to social dynamics and broader societal influences, including stigma and timing constraints, which extend beyond the more immediate considerations of site and environment. Difficulties arising from high expectations, judgmental attitudes, and lack of understanding, which are at times compounded by sensory overload, were also expressed by participants.

Moving into specific scenarios as exemplars, Hannah (S28) shared the discomfort of going out in public places due to social stigma: "*A lot of public places are difficult for him because he doesn't self-regulate very much and he gets stared at, frankly*". DeeJay (FS20) added their firsthand perspective: *"There is, of course, the attitudinal component, that sort of the gaze, do what it's like almost the sort of clinical gaze that, you know, Foucault talks about. It is pervasive in these spaces as well. So there's, you know, there is still pressure, I think, to mask"*.

The insights from participants emphasized the importance of fostering a sense of belonging for diverse neurotypes in society, without the fear of oppression or stigma. Design interventions, such as artistic enhancements and developing sensory-responsive environments, may contribute to creating inclusive and welcoming spaces for neurodivergent individuals. However, larger social issues and cultural norms were also suggested to play an impactful role, influencing the neurodiverse community's utilization of built environments.

Overall, these findings indicate that societal factors are intertwined with space and place, impacting the access to and use of space by the neurodiverse community. The qualitative insights from this study build an imperative for a greater societal shift, which extends beyond the realm of landscape and urban design interventions to enhance inclusion in society and to address its antithesis: exclusion.

3.1.14. Accessibility and Inclusion

Study participants emphasized the need for public-facing environments to be sensorially accessible. Essential accommodations highlighted included provisions for pets and support animals, facilitating multi-generational use, and providing gender-neutral facilities, including bathrooms for caregivers and family support. The importance of involving neurodiverse user groups in planning and design processes was emphasized to ensure their equitable representation. A prominent finding was the universal benefit of inclusive design and accessibility in outdoor built environments, which, according to the majority of participants, would better serve both neurodivergent and neurotypical individuals, lending to a holistic interpretation.

As a brief illustration of this perspective, Manni (P1) shared: "*If you design a neuro-inclusive space, it's also nice for everyone else, you know? There's nothing that's good for specifically someone with autism that someone without autism wouldn't also enjoy. But there is vice versa of that... So you might as well design things with a neuro-inclusive mindset. And then everyone will also either consciously or unconsciously appreciate the soft lighting, color scheme, or flow of the place... it's just more natural*". Gabriel (PF17) echoed Manni's sentiment, expressing, "*I think it's important. I think it has impacts beyond just the neurodivergent community... If we design spaces with sensitivities and sensitive people in mind, it will also benefit the less sensitive people in the population*".

Centering the needs of marginalized communities and designing from those margins emerged as a pivotal theme among study participants. While aligning with the Design From the Margins (DFM) model initially conceptualized within the UX industry, DeeJay (FS20) voiced the collective advocacy for *"designing outside the statistical dispersion"* and prioritizing marginalized groups who are frequently overlooked. In the context of neurodivergence, this necessitates a shift in perspective to accommodate the needs of divergent bodies. Highlighting the absence of such considerations, DeeJay shared: *"There's none of those spaces, public spaces that seem to consider these divergent bodies"*. They suggested, *"Instead of designing for the median... Think about who's way out here [referencing the edges with her hands]. What would that look like? If we were designing to get people like that, that are never considered because they're nowhere even close to the center"*.

4. Discussion

The primary research question of this qualitative study asked, "How do individuals with lived experience of neurodivergence, particularly those belonging to neurominority groups such as autism, ADHD, and dyslexia, perceive the relationship between designed outdoor environments and sensory sensitivities (hypo and hyper) experienced by neurodivergent individuals?" This study delved into the sensory needs and preferences of neurodivergent individuals in outdoor built environments by examining participants' lived experiences and perceptions regarding sensory sensitivities (both hypo and hyper) from firsthand, secondhand, and professional perspectives. Through this exploration, enhanced comprehension of how environmental factors affect the interactions and participation of diverse neurotypes in public-facing outdoor spaces emerged.

Following the establishment of the findings' significance through thematic narrative analysis, the table "Emergent Themes: Thematic Narrative Analysis" (refer to Table 3) presents a concise summary of the major emergent themes identified in this study pertaining to participants' lived experiences with neurodiversity and atypical sensory systems.

Table 3. Emergent themes: thematic narrative analysis summaries.

Emergent Theme	Brief Summaries
Individual factors	*INSIGHTS:* This study covered both hypo- and hyper-sensitivities across the sensory modalities observed. These atypical experiences encompassed all senses represented in this study and were reported by individuals with various diagnoses, neurodivergent identities, and perspectives (firsthand, secondhand, and professional). The concept of sensory stacking also emerged, clarifying the effect of multiple stimuli on sensory overload. *IMPLICATIONS FOR DESIGN:* • **Address sensory stacking by minimizing sensorial intrusions**: Environments with multiple sensory pollutants should be carefully designed to reduce unnecessary intrusions. Kaplan and Kaplan [35] discussed the restorative effects of soft fascinators in reducing mental fatigue and restoring attention, which could mitigate the impacts of sensory stacking for individuals with sensory sensitivities. • **Acknowledge and accommodate atypical sensory profiles in landscape and urban design**: Design should be responsive and adaptable across different sensory modalities and stimulation levels to accommodate atypical sensory profiles. *DISCREPANCIES AND FUTURE RESEARCH DIRECTIONS:* Although this study highlighted the complex sensory experiences of neurodivergent individuals, there remains a gap in effectively applying research findings in practical and impactful design solutions.
Personal factors	*INSIGHTS:* Participants varied in how they described their sensory experiences within environmental contexts. Some provided detailed descriptions, while others were brief and experienced challenges in communicating their sensory experiences clearly. Participants noted the individuality of neurodivergent experiences, including significant variations in how ADHD, dyslexia, and autism manifest in different individuals. There were also concerns about the potential for overlooked (missed diagnoses) and misdiagnosed conditions in neurodivergent individuals. Many participants found the semi-structured interviews to be opportunities for self-discovery.

Table 3. *Cont.*

Emergent Theme	Brief Summaries
Personal factors	*IMPLICATIONS FOR DESIGN:* • **Participatory input**: Acknowledge and accommodate individual neurodivergent communication styles and experiences to shape non-prescriptive design approaches. *DISCREPANCIES AND FUTURE RESEARCH DIRECTIONS:* The variability in how participants articulated sensory experiences, alongside the breadth of potential personal factors impacting user experiences, necessitates enhancing design communications and community engagement strategies to better accommodate neurodivergent perspectives in design processes.
Sensory affordances	*INSIGHTS:* The role of sensory affordances, which are features that can either support or hinder sensory experiences, in designed environments was thematically highlighted by study participants, along with their impact on the neurodiverse community in both distressing and supportive contexts. There was a noted scarcity of sensorially accommodating outdoor environments, such as in active transportation, streetscapes, parks, and schools. There was also an identified need to include considerations for proprioception, vestibular, and interoception in design. *IMPLICATIONS FOR DESIGN:* • **Designing with sensory affordances**: Intentional design consideration of sensory affordances is essential for mitigating environmental impacts on user experiences. James J. Gibson's Theory of Affordances, which primarily addresses general environmental interactions, offers a fundamental framework for understanding sensory perceptions and actions within the built environment [25,36]. Extending this theory could help tailor environmental designs to better meet the sensory needs of neurodivergent individuals. • **Addressing sensory overwhelm and underwhelm**: Account for both hypo- and hyper- sensitivities in design. • **Extend sensory design considerations**: Beyond the classic five senses, include affordances for the foundational senses. This extension is supported by the literature advocating for inclusive design that encompasses these senses [7]. *DISCREPANCIES AND FUTURE RESEARCH DIRECTIONS:* While Gibson's Theory of Affordances outlines how environments can influence behavior, it lacks specific applications for neurodiverse populations, indicating a significant gap in its scope. The findings suggest an expansion of the theory to include sensory affordances tailored to the unique needs of neurodivergent individuals.
Benefits of outdoor environments	*INSIGHTS:* Participants highlighted experiences of distress caused by anthropogenic sensory triggers, contrasting them with calming multi-sensory experiences with natural elements such as greenery, biodiversity, and aquatic features. Many reported sensory reliefs in outdoor settings compared to indoor settings. While natural spaces were highly valued, including in urbanized environments, challenges such as stinging insects and tactile qualities were also noted, illustrating the complexity of sensory experiences in these environments. *IMPLICATIONS FOR DESIGN:* • **Leveraging natural and geological features**: Integrate bio-stimuli and geo-stimuli to alleviate sensory distress associated with both indoor and outdoor environments. The relevant literature [37,38] states that natural elements can provide enriching sensory experiences that are not aversive. Additionally, research [39–41] has documented that nature not only reduces stress, but also enhances overall well-being. • **Incorporate biophilic design**: To mitigate sensory pollution, for example, using water features for sound masking. This approach is supported by E.O. Wilson's theory of biophilia [42], which posits an inherent human affinity for nature, aligning with evolutionary predispositions. • **Balancing natural elements**: The negative cases identified in the study highlighted the need to carefully balance natural elements in design to minimize potential sensory irritants. *DISCREPANCIES AND FUTURE RESEARCH DIRECTIONS:* Further investigation is recommended to comprehensively understand optimal nature-based designs and nature as a sensory support for neurodiverse populations.

Table 3. *Cont.*

Emergent Theme	Brief Summaries
Ambient environmental factors	*INSIGHTS:* The study revealed perceived relationships between ambient environmental factors, such as noise pollution, light sensations, atmospheric conditions (sensitivity to extreme temperatures), and environmental scents and allergens, and the experiences of neurodiverse user groups with sensory sensitivities. Notably, noise pollution emerged as a prominent cause of sensorial distress in outdoor environments. Participants consistently preferred geo-stimuli and bio-stimuli over anthro-stimuli. *IMPLICATIONS FOR DESIGN:* • **Select sites that mitigate sensory irritants and sensory pollution**: Choose sites where natural landscape features and topography can be leveraged to minimize sensory irritants. • **Limit anthropogenic stimuli and introduce bio-stimuli and geo-stimuli**: Introduce natural elements (bio-stimuli and geo-stimuli) to enhance the ambient sensory environment. • **Select and strategically place materials that absorb sound**: Materials that absorb sound can reduce noise pollution and echoes. This strategy is supported by the literature [7,26] as an effective measure for enhancing sensory comfort, particularly for autistic children. • **Design for comfortable atmospheric conditions**: Incorporating features like shaded areas, windbreaks, and misters to manage temperature extremes is a strategy supported by the existing literature [32,37]. • **Optimize lighting conditions**: Employ natural light and select artificial lighting that mimics natural light, while avoiding harsh and flickering lighting. • **Choose scents that provide pleasant, non-overpowering aromas**: Carefully select scents to avoid synthetic fragrances and allergenic plants. This practice addresses olfactory sensitivities, as noted in autism-focused literature [7,32,43]. *DISCREPANCIES AND FUTURE RESEARCH DIRECTIONS:* While the referenced literature primarily focuses on design for autism, especially in children, this study extended these insights to a wider range of neurodiverse populations and in outdoor contexts. This study presented the use of bio-stimuli and geo-stimuli in sensory responsive design, opening up new avenues for research.
Materiality	*INSIGHTS:* This study revealed connections that neurodivergent individuals with sensory sensitivities experience with materiality. A preference patter for material authenticity (natural materials), softscape materials, and subdued/neutral or natural colors, over artificiality, excessive hardscapes, and extreme color palettes emerged. Considerations for stable walking surfaces and caution regarding material toxicity were also emphasized. Chrome was found to be off-putting by several study participants. *IMPLICATIONS FOR DESIGN:* • **Prioritize authentic materials**: Choose materials that retain their natural characteristics, such as wood, stone, and natural fibers, over synthetic alternatives. Avoid artificial materials like chrome when possible. • **Utilize natural and muted neutral tones**: Employ natural, low-saturation, and neutral colors to create calming environments, as also suggested by Gaines et al. [33] and Biel and Peske [7]. • **Use lighter shades on materials to mitigate heat absorption**: Lighter shades can help reduce heat absorption, improving thermal comfort and usability of outdoor spaces. • **Strategically incorporate brighter colors**: Ensure these are not overstimulating and are balanced as visual cues to aid safe navigation, enhancing clarity and visual accessibility. • **Achieve a balance between hard and soft materials**: Give priority to soft elements where appropriate, while opting for stable, non-slip materials for walking surfaces. • **Introduce a variety of textures**: Provide sensory feedback and enrich tactile experiences. According to Clouse et al. [3], varied textures are essential for sensory stimulation. • **Choose non-toxic materials**: This aligns with cautions by Sachs [32] and Herbert [44] against the use of toxic materials that could be accidentally ingested. *DISCREPANCIES AND FUTURE RESEARCH DIRECTIONS:* While the existing literature largely focuses on neurodiverse needs within indoor settings and often centers on autistic children, this study expanded the scope to include outdoor environments and a wider range of neurodivergent groups, including ADHD, autistic, and dyslexic adults. Additionally, the negative reception of chrome suggests an area for further exploration and potentially challenges prevailing design norms.

Table 3. *Cont.*

<table>
<tr><th>Emergent Theme</th><th>Brief Summaries</th></tr>
<tr><td>Spatial design</td><td>INSIGHTS:
Emphasis was placed on spatial layout considerations in the design of neuro-inclusive outdoor environments. This study emphasized incorporating a variety of sensory opportunities tailored to a range of spatio-sensorial needs, minimalistic design, a balance between openness and enclosure, as well as considerations for potentially overstimulating and layered sensory challenges related to dynamic landscape elements and proxemics (social proximity).

IMPLICATIONS FOR DESIGN:
● Offer both sensory-rich and sensory-minimal opportunities: Design spaces that allow individuals to modulate their sensory engagement while providing smooth transitions—an aspect outlined for ASD users as documented [43–45].
● Adopt minimalistic design to reduce sensory overload: As supported by Gaines [33], focused on autism.
● Balance openness and enclosure: A design strategy that aligns with “Prospect Refuge Theory”, which suggests that individuals universally prefer areas where they can look out from a safe vantage [46].
● Incorporate proxemics to manage social distances and dynamic elements: A relatively underexplored area in neurodivergent research.

DISCREPANCIES AND FUTURE RESEARCH DIRECTIONS:
While the literature has primarily focused on autism, it may apply to other neurodiverse user groups like ADHD and dyslexia. Further, the discussion around proxemics and dynamic landscape elements in neurodiverse groups is not extensively covered in existing studies, indicating a gap that this research addressed, and suggesting a direction for future scholarly inquiry.</td></tr>
<tr><td>Navigating environments</td><td>INSIGHTS:
Study insights highlighted neuro-atypical challenges with navigation in unpredictable and informal environments, sites lacking directional cues, confusing and unclear wayfinding, and poor circulation planning. A novel concept, “solar-based navigation”, was introduced, suggesting that sunlight obstructions may impact the internal sense of direction for some neurodivergent individuals.

IMPLICATIONS FOR DESIGN:
● Establishing formality and predictability: Introducing explicit formality and predictability in landscape and urban design can provide necessary structure and guidance. The literature emphasizes the importance of predictability in environments for autistic individuals [32,38,43,44].
● Clear circulation patterns: Developing clear circulation patterns to minimize confusion and enhance navigational ease is also indicated by the current body of literature [33,38,43,44].
● Using distinct landmarks and visual cues: Employing distinct landmarks and visual cues, such as color and icons, as orientation aids can support navigation for neurodiverse user groups.
● Incorporating natural cues: Consider the use of existing natural cues, such as natural light, for orientation.

DISCREPANCIES AND FUTURE RESEARCH DIRECTIONS:
While the existing literature predominantly focuses on autism and children, this study expanded the scope to include other neurodivergent user groups with sensory sensitivities. The concept of solar-based navigation suggests a novel area of research.</td></tr>
<tr><td>Pedestrian-centric transportation</td><td>INSIGHTS:
This study identified areas in current transportation systems that participants perceived as inadequate for neurodiverse user groups. These included exposure to overwhelming anthropogenic stimuli, a lack of comfortable seating, insufficient softscape in terminals, excessive noise, movement of traffic alongside active transportation systems, as well as safety concerns due to scarce separation from traffic, and confusing layouts with ineffective wayfinding.

IMPLICATIONS FOR DESIGN:
● Pedestrian-centric environments: Prioritize pedestrians over vehicle traffic and minimize vehicle-centric elements.
● Public transit and active transportation systems: Enhance logical connectivity and include features such as softscapes, barriers from urban sensory stressors, and setbacks from traffic.</td></tr>
</table>

Table 3. *Cont.*

Emergent Theme	Brief Summaries
Pedestrian-centric transportation	• **Pathway design for enhanced accessibility**: Design pathways that are wide, incorporate gradual turns, and ensure ample visibility. • **Rest areas away from sensory stressors**: Position seating and rest areas away from busy paths and traffic. *DISCREPANCIES AND FUTURE RESEARCH DIRECTIONS:* The existing literature on urban design minimally addresses the sensory needs, safety, and accessibility requirements of neurodiverse populations in transportation systems. Future studies could aim to close this identified research gap.
Sensorimotor movement	*INSIGHTS:* The findings suggest that sensorimotor experiences in designed environments are integral to the well-being and inclusion of individuals with sensory processing challenges in outdoor built environments. Engaging in activities such as climbing, running, swinging, and receiving vestibular input, including multi-generational play, were seen as beneficial for those with sensory sensitivities, aiding sensory regulation and enhancing engagement. *IMPLICATIONS FOR DESIGN:* • **Craft movement-friendly environments**: Enhance sensory regulation and engagement for users of all ages and sizes by designing environments conducive to movement. • **Incorporate physically engaging features**: Include fitness trails and multi-generational play equipment such as swings and climbing structures to enhance sensory regulation and engagement. The literature supports the integration of dynamic activities, highlighting that they improve coordination, motor skills, and balance, and can benefit a broad range of users [7,38,43,47]. • **Integration with stationary environments**: Explore how movement-friendly settings can complement static environments like workplaces and academic settings. *DISCREPANCIES AND FUTURE RESEARCH DIRECTIONS:* While the existing literature robustly covers autism and children, there is a notable gap regarding other neurodiverse groups and the multi-generational dimension of sensorimotor design. Future research could broaden insights into how movement-oriented environments can support a range of neurodiverse populations across all age groups.
Safety	*INSIGHTS:* The study emphasized the perceived importance of safe landscapes for both sensory seekers and sensory avoiders, focusing on features such as explicit boundaries/perimeters from hazards and unobstructed pathways. Study participants highlighted the importance of both objective safety and a sense of safety. *IMPLICATIONS FOR DESIGN:* • **Clearly marked safe zones**: Implement clearly marked zones that facilitate quick access to safe spaces when needed and ensure paths are free from obstacles. • **Sensory buffers**: Integrate features that mitigate sensory intrusions. • **Explicit perimeters and physical buffers**: Establish boundaries like thick vegetation around potential hazards, such as bodies of water and busy streets. The current body of knowledge [32,37,43,44,48] supports the creation of environments with defined boundaries and containment, which enhance safety and control—vital for sensory seekers—to help prevent elopement and support autonomy. *DISCREPANCIES AND FUTURE RESEARCH DIRECTIONS:* While the literature provides substantial guidance on environmental safety features for autistic individuals with higher support needs, there remains a gap in comprehensive studies focused on broader neurodiverse populations and multi-generational groups. Future research should explore the scalability of these design strategies across different neurodiverse groups and examine the long-term impacts on their safety and autonomy in designed outdoor environments.
Refuge	*INSIGHTS:* The necessity for refuge (sensory and social) from stimuli and opportunities for self-regulation and sensory reset among the neurodiverse community was consistently emphasized. The lack of suitable refuges emerged as a notable sensory barrier, highlighting both the current gap of such places and the importance of establishing sensory refuges for equitable access to public amenities/assets for neurodiverse user groups.

Table 3. *Cont.*

Emergent Theme	Brief Summaries
Refuge	*IMPLICATIONS FOR DESIGN:* • **Integration of sensory refuges**: Incorporate sensory refuges adjacent to highly stimulating environments to offer opportunities for self-regulation during moments of sensory overload. The need for low-stimulation spaces has been documented by Gaines et al. [33] and Mostafa [45]. • **Influence of Prospect-Refuge Theory**: Implement refuge designs guided by the Prospect-Refuge Theory, which posits that environments providing security and observation opportunities can enhance well-being [49]. • **Nature-inspired elements and directed focal points**: Use nature-inspired designs and directed focal points, such as greenery and water features, to offer relief from urban sensory overload. This approach is supported by Kaplan's theories on the restorative effects of nature, suggesting that environments with soft fascinations help alleviate mental fatigue [49]. • **Adaptability of refuges**: Ensure that refuges are adaptable to diverse contexts, as they can vary greatly in shape, size, and sensory attributes. *DISCREPANCIES AND FUTURE RESEARCH DIRECTIONS:* Further studies are required to explore the benefits of sensory refuges in designed outdoor environments, including how they can be positioned adjacent to or integrated into highly stimulating environments, and their effectiveness across neurodiverse populations.
Human settlement types	*INSIGHTS:* Desirable amenities and resources, such as social services, adequate public transit, and medical care, as well as barriers—primarily anthropogenic sensorial intrusion and transportation-related challenges—were perceived as evident across human settlement types (rural, suburban, and urban) in relation to neurodiverse experiences. *IMPLICATIONS FOR DESIGN:* • **Tailored planning**: Adapt urban, suburban, and rural development plans to meet the specific sensory needs of neurodiverse populations. This includes ensuring equitable access to essential resources such as outdoor spaces, support services, and transportation systems. • **Engagement with neurodiverse stakeholders**: Actively involve local neurodiverse communities in planning processes to better identify and address the unique challenges they face in different types of settlements. *DISCREPANCIES AND FUTURE RESEARCH DIRECTIONS:* This theme is relatively unexplored, presenting an opportunity for groundbreaking research on the intersection of human settlement types and neurodiverse experiences.
Social environments	*INSIGHTS:* This study brought attention to challenges experienced by neurodivergent individuals in social environments such as gathering places, event spaces, academic settings, and workplaces. These challenges include stigma, discrimination, and time-related stress. A shared goal emerged, advocating for a wider societal transformation in cultural norms. *IMPLICATIONS FOR DESIGN:* • **Early access and flexible participation**: Implement early access and flexible options for participation in social settings to enhance inclusivity. • **Supportive social landscapes**: Design social environments that promote sensory well-being, such as providing retreat spaces (alcoves, separate areas, or quiet sections with partitions) to allow individuals to manage overwhelming social situations. This approach encourages choice, comfort, and positive social interactions, supported by literature [1,7,31,37,43,45]. • **Awareness and advocacy**: Enhance awareness, education, and advocacy efforts to foster inclusivity and acceptance in social settings. Integrating educational components and representative art into landscapes can further this goal. *DISCREPANCIES AND FUTURE RESEARCH DIRECTIONS:* Research on specific design interventions for landscapes and urban environments that meet the social needs and preferences of neurodivergent individuals in social settings remains sparse. Future studies could aim to address these gaps.

Table 3. *Cont.*

<table>
<tr><th>Emergent Theme</th><th>Brief Summaries</th></tr>
<tr><td>Accessibility + Inclusion</td><td>INSIGHTS:
This qualitative study examined patterns related to inclusive design and accessibility for individuals with diverse neurological systems in outdoor environments. Participants expressed the need for support animal accommodations, gender-neutral bathrooms, and multi-generational design approaches. They also emphasized recognizing divergent perspectives, involving the neurodiverse community in the design process, and prioritizing the needs of marginalized communities.

IMPLICATIONS FOR DESIGN:
• Active user involvement: Involve users in the design process. Sensory mapping and community/stakeholder workshops are engagement tools that could be used, among others. The literature indicates that such engagement is crucial for creating environments that support health, well-being, and inclusivity [43,50].
• Incorporate neurological variations: Design for neurological diversity to accommodate both neurodiverse and neurotypical populations.
• Gender-neutral and multi-generational features: Implement gender-neutral bathrooms, multi-generational design, and support animal accommodations, to improve neuro-atypical accessibility.
• Center marginalized communities: Employ Design from the Margins (DFM) approaches [51] that center marginalized individuals throughout the design process, an approach that seeks to create solutions beneficial to a broad range of users by designing to the edges rather than to the central majority.

DISCREPANCIES AND FUTURE RESEARCH DIRECTIONS:
Further research is needed to broaden inclusive design principles and accessibility considerations to encompass a wider range of disabilities, such as invisible and sensory.</td></tr>
</table>

4.1. Key Sensorial Barriers

In reviewing the thematic narrative analysis, a distinction emerged between the access needs and sensory preferences of neurodivergent individuals. Certain sensory preferences expressed by some study participants were presented as essential access needs by others, indicating that the line between sensory needs and preferences blends and fluctuates depending on the site's context, intended uses, and the unique requirements of each individual. With this disclaimer in mind, the more critical needs identified related to environmental factors are represented as barriers in this discussion.

Key sensorial barriers identified included, but were not limited to:

- Ambient environmental factors, primarily attributed to anthro-stimuli such as artificial lighting, scents, and extreme temperatures, were found to be barriers. Noise pollution, especially from traffic and crowds, was commonly reported as challenging in both active and passive environments.
- The compounding sensory challenges faced in highly stimulating busy areas, where refuges that promote self-regulation are lacking, were a key observation in this study.
- The study identified that navigating environments with inadequate wayfinding support, informal layouts, unpredictable elements, and a lack of intuitive circulation exacerbates moments of sensory distress and limits access.
- Safety challenges, such as unsafe walkways, landscapes with potential hazards like large bodies of water and busy streets, and areas with increased navigational challenges, were highlighted as barriers to use. Emphasis was also placed on the importance of both objective safety and a subjective sense of safety.
- Participants highlighted a notable limited availability of accessible public and community spaces that provide sensory affordances.
- The absence of opportunities for sensorimotor movement, such as vestibular and proprioceptive input, was highlighted as a barrier.
- A lack of sensory-friendly environments that offer suitable options for the neurodiverse community and family gatherings represented additional access barriers.

- While many of the prominent sensorial access barriers can be addressed through design interventions, it is important to acknowledge that social and societal barriers rooted in stigma and a lack of understanding regarding social environments for those with sensory sensitivities were also attributed to be barriers. Addressing these issues may require a societal shift beyond the scope of landscape and urban design interventions to foster greater access and neuro-inclusion.

The barriers outlined in the preceding paragraphs transcend matters of preference; they are deeply connected to the concept of spatial access for neurodivergent individuals in built environments, emphasizing that mere physical entry does not necessarily equate to genuine or functional access. Seeking a deeper understanding of these barriers across various landscapes is important to better understand how we can enable the participation of neurodiverse user groups in the places we design and build.

4.2. Key Sensorially Supportive Elements

In this study, sensorially supportive elements in the landscape and urban design for the neurodiverse community were unearthed. While the subsequent discussion does not cover all sensorially supportive elements identified in the study, it highlights the more prominent ones.

Key sensorially supportive features identified included, but were not limited to:

- Outdoor settings, especially with access to bio-stimuli and geo-stimuli, were expressed to be sensorially supportive, i.e., pleasing and comforting to the senses, compared to public-facing indoor spaces and outdoor locations with heavier anthro-stimuli present. Participants stressed the importance of integrating nature into urbanized environments to meet their sensory needs.
- Green spaces like forests, gardens, nature parks, and trails, as well as areas with aquatic features such as waterfalls and lakes, were highlighted. Soothing water sounds were especially acknowledged for their therapeutic sensory benefits.
- Opportunities to interact with wildlife were highlighted as beneficial, including sounds like birdsong or rustling leaves stirred by the movement of small critters.
- The positive impact of incorporating nature-based and authentic materiality on sensory experiences was noted.
- The use of muted and natural color choices was emphasized.
- The strategic balance between hardscapes and softscapes to foster a harmonious sensory setting was discussed.
- The incorporation of design features that favor natural lighting while steering clear of harsh, overhead, and flickering lights was widely recommended.
- Sensorimotor movement and engagement opportunities that accommodate neurodivergent individuals of all ages, body types, and abilities were suggested.
- Effective navigation in environments, facilitated by clear wayfinding, pedestrian-focused access, and intuitive circulation, was highlighted.
- Spatial designs that offer varied options and special consideration for meeting different sensory needs and activities, entailing a thoughtful balance between open and enclosed spaces, attention to proxemics and dynamic elements, and the adoption of minimalistic design principles to move beyond monotonous design approaches, were expressed as supportive.
- Incorporating elements like sensory and social refuges that provide opportunities for self-regulation and draw from nature-based design strategies was suggested to support sensory well-being. These sensory refuges could draw from therapeutic and restorative design techniques to mitigate anthropogenic sensory stressors and may prove to be timely and tangible interventions to counterbalance overstimulating built environments.
- For ambient materiality, supportive strategies like employing ambient buffers, thoughtful site selection to avoid sensory intrusion, and authentic and soft material choices and strategic placement were recommended.

- Sensory support for safety issues/hazards included clear perimeters, physical buffers from hazards like thick vegetation, and strategic design interventions such as setbacks in street planning, all aimed at improving safety, autonomy, and freedom for the neurodiverse community, especially in active transportation and park settings.

Within the scope of this qualitative study, the discussion, while not exhaustive, recognizes the significance of embracing multi-sensory landscapes. This involves integrating sensorially supportive design interventions and elements that cater to a broader spectrum of sensory modalities, potentially benefiting both neurodiverse and neurotypical users.

4.3. Site Considerations

So, which sites should be addressed? The proposition here is that public-facing sites, especially those essential for meeting daily needs and full participation in society, should be prioritized currently for evaluation and intervention. While transportation systems require thorough investigation into access issues, many other outdoor built environments also necessitate careful examination, like commercial environments, work facilities, academic and school settings, and recreation areas, among others that are essential for meeting the demands of daily life and requirements for personal health and well-being.

Assessing the existing multi-sensory aspects of a proposed or existing site for development (or redevelopment) involves considering both sensorially supportive features and existing sensorial barriers. Additionally, it entails determining how the site can provide sensory affordances tailored to the distinct sensory needs of neurodiverse user groups that align with the site's intended uses. While some landscapes may already accommodate atypical sensory needs for their intended uses, requiring minimal intervention, others may be in sensorial disarray, such as with heavily urbanized environments.

When evaluating a new development or redevelopment project, several questions come to mind. Here are just a few:

- Are there multi-generational recreation opportunities for neurodiverse user groups in the community/area—a sensory-responsive place to exercise, gather, and play?
- Is the site associated with a medical center, shopping mall, work setting, event space, or academic environment? If yes, are there sensory refuges from overstimulating stimuli available, and are accessible wayfinding and active transportation systems in place to reach them?
- Is it a site with a sensory-rich biophilic environment featuring easily navigable wide trails, clear wayfinding, smooth transitions, and buffers from anthropogenic sensorial intrusions and safety hazards? For this hypothetical site, the intervention may be as simple as communicating its pre-existing availability for those with atypical sensory needs to the intended user groups.

To determine appropriateness, it is recommended to consult with the local neurodiverse community, their allies, and experts.

4.4. Broader Applications

Broader applications of the findings of this study and the proposed potential design interventions have been considered as they relate to other populations and circumstances. The heightened focus on sensory experiences among neurodivergent user groups, covering both hypo- and hyper-sensitivities, has the potential to illuminate how sensory challenges faced by other populations can be addressed. In addition to the focus groups of this study (ADHD, autistic, dyslexic), there are other populations who may have sensory-related challenges, such as those experiencing oppositional defiant disorder, depression, anxiety, OCD, bipolar disorder, Tourette syndrome, fragile X syndrome, fetal alcohol syndrome, cerebral palsy, down syndrome, dyspraxia, apraxia, and other disabilities [7]. It is important to note that trauma is also understood to have a relationship with sensory processing challenges, which may extend to individuals in recovery centers, refugee camps, and other contexts.

Neurodivergent individuals with sensory sensitivities are not confined to a certain socioeconomic status, gender, race, age, political affiliation, religious affiliation, geographic location, or other demographic variable(s) that can act as dividers; the atypical sensory experience bridges all demographics. These individuals may also face overlapping equity issues, sharing common ground with other minority, marginalized, and oppressed groups. The intersection of identities, such as being autistic and belonging to a racial minority, can compound sensory barriers, further limiting individuals' ability to fully engage with and participate in their environments. For instance, they may encounter additional hurdles in accessing resources, sensorially supportive outdoor environments, or accommodations tailored to their sensory needs.

4.5. Theoretical Connections and Existing Guidelines

The qualitative research findings align with and support various established theoretical frameworks, drawing upon Ulrich's exploration of the therapeutic benefits of nature and finding resonance with Kaplan's Attention Restoration Theory, Wilson's concept of Biophilia (including biomimicry), and the Prospect-Refuge Theory. These theoretical frameworks are enriched by the qualitative insights from this study, which also advance the discourse on neuro-inclusive design and sensory support.

Throughout this study, it became evident that the established design guidelines presented in the comprehensive literature review [11] were not contradicted by this study's findings. Instead, there were numerous overlapping considerations, such as sensory zoning, despite those specific guidelines being primarily intended for autistic children and children with SPD, with some solely focused on indoor environments. These intersections between research findings and existing guidelines validate and reinforce the potential of informed design solutions to effectively transfer across both environment types and disciplines while adequately serving the neurodiverse community. However, the findings of this study do indicate that prescriptive guidelines may not be suitable for the design and planning of many outdoor built environments.

4.6. Discussion Summary

Landscapes are multi-faceted, serving as the physical backdrop and catalyst where daily activities unfold. They influence not only factors impacting health and livelihood, but they also function as dynamic platforms for connection, understanding, and shared experiences. In doing so, they carry notable meaning for many communities and individuals, providing a sense of belonging and autonomy and shaping their identities within the fabric of society.

Built environments can also be designed to either include or exclude access; exclusive design approaches carry implications for equity. This research uncovered numerous consequences resulting from the oversight of not considering atypical sensory systems in design, leading to barriers and limitations that impact full participation in society and access to public assets, amenities, resources, and opportunities for the populations represented in this study. Along the same lines of inclusion and exclusion, enabling contrasts disabling.

Sensory responsive design approaches hold the potential to complement health equity and enable a wider range of neurotypes to fully engage and thrive in their surrounding environments. In light of this study's findings, the "Sensory-Responsive Environments Framework" has surfaced as a versatile design lens to address atypical sensorial needs, particularly focusing on overlooked "invisible" disabilities in landscape and urban design. This will be introduced in the next section.

While this study has provided informative insights, it has also raised many unresolved questions, unveiling unexplored terrain awaiting further discovery. Although it marks a significant step in advancing the conversation, much more remains to be explored in this emerging field.

4.7. Theoretical Framework: Sensory Responsive Environments Framework (SREF™)

The study findings are evident: a one-size-fits-all approach is neither accommodating nor optimal when addressing heightened and/or diminished sensory sensitivities in designed environments. To create spaces that reflect and cater to the multiplicity of human experience and respond to atypical sensory needs and preferences, it is suggested to adopt context-sensitive, flexible, and iterative design processes, rather than prescribing a homogeneous method. Emphasizing a human-centered approach, acknowledging the complexities of various sensory modalities, and encouraging the participation of diverse user groups can help ensure the efficacy of the design solutions. Additionally, understanding the layered, site-specific contexts and intended uses of the site being designed, along with the existing multi-sensory qualities of surrounding environments, is recommended. Adaptability to accommodate evolving research, language, and design trends is another consideration to remain mindful of when designing to accommodate and support the neurodiverse community in built environments.

To integrate this interpretation of the study findings into an adaptable tool, the Sensory-Responsive Environments Framework (See Figure 3) was crafted as a design lens through which to "see" the "invisible" in order to support atypical sensory needs, encapsulating four key principles identified from the study: Design From the Sensorial Margins (DFSM), sensory zoning, nature-based approaches, and community involvement (co-design). Integrating these principles leads to a sensory responsive design approach that enhances sensory affordances and enables greater participation of the neurodiverse community in built environments.

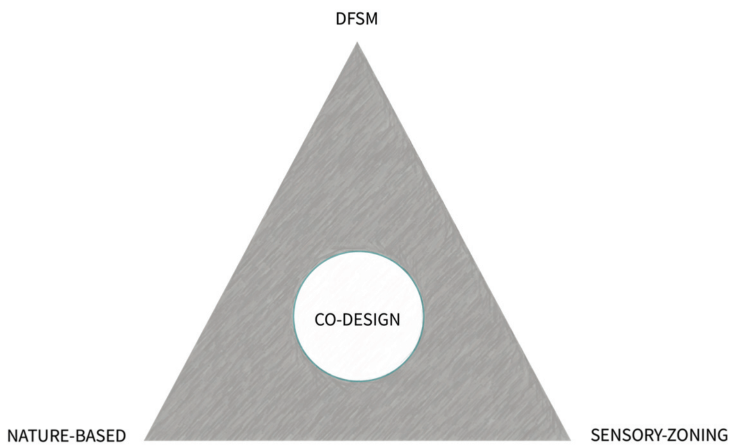

Figure 3. Sensory Responsive Environments Framework™. Created by the author.

4.7.1. Design from the Sensorial Margins (DSFM)

Designing From the Margins (DFM) [51] involves centering marginalized communities and moving away from designing exclusively for the majority. In the context of neurodivergence, it entails comprehensive understanding and consideration of neurodiverse needs and accommodating sensory extremes, encompassing both hypo- and hyper- sensitivities (see Figure 4). This approach is poised to benefit not only those on the margins, but also individuals at different points along the sensory spectrum between hypo and hyper, in an aim to foster inclusivity throughout the entire range of user experiences with regard to the senses.

Adapting Rigot's DFM approach [51] shows potential for addressing the range of atypical experiences scattered between the sensory extremes. For instance, in scenarios where sensorial intrusion may be discomforting but somewhat manageable for some, it may represent firm access barriers for others. Designing from that sensory edge can improve the experience for both hypothetical users and provide a focal point for designers to start working from. By focusing on the edges of sensory spectrums and tailoring solutions to those specific needs, we enhance our ability to accommodate a wider range of user experiences and better serve individuals who fall at various points within the sensorial prism.

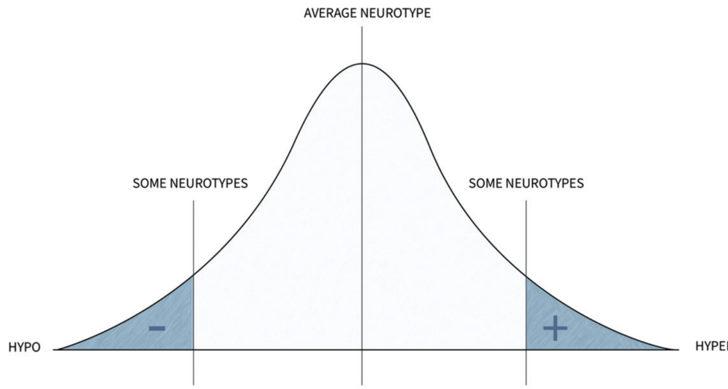

Figure 4. Design From the Sensorial Margins. Adapted from Afsaneh Rigot's Curve Graph [51]. Created by the author.

4.7.2. Sensory Zoning

Sensory zoning is an important addition to DFSM, addressing both sensory avoidant and sensory seeking needs and responses. Given the complexity of designing for diverse sensorial needs and the less flexible nature of public-facing outdoor environments as compared to more personalizable interior spaces, a one-size-fits-all solution and explicitly adaptable environments are not feasible, warranting a multifaceted approach from the onset of site development. This strategy can offer varied sensory affordances and implicit adaptability and respond to the multi-sensory environment of the site being developed. In simple terms, it provides different options for users to choose from.

Incorporating sensory zoning into the framework was informed by a synthesis of study findings and a comprehensive review of the existing literature [32,33,45], along with insights from Dr. Amy Wagenfeld [17]. Study participants emphasized the importance of diversified landscapes with various sensory opportunities, aiming to provide a balanced range of experiences for differently wired users. Although the term "sensory zoning" may not have been explicitly used by all, various sources [1,7,32,33,43,45,52] have closely aligned with the concept by advocating for the creation of social spaces that encourage choice, comfort, and positive social interactions in relation to autism and sensory processing challenges.

Sensory zoning in the design of outdoor built environments is a potential avenue to accommodate various landscape types, uses, and sensory needs. For example, a sensory responsive park might designate an area specifically tailored for sensory-seeking activities, such as multi-generational playgrounds and swings, alongside a range of sensory affordances. Simultaneously, it could provide a nearby sensory refuge, informed by therapeutic design, away from noise pollution and other anthropogenic sensory stressors, allowing for moments of sensory calm and opportunities for self-regulation in instances of sensory overload. This approach could enable individuals with both hypersensitive and hyposensitive needs, as well as those who need to mitigate a range of sensory experiences, to have more suitable access to the park. By designing from the sensory margins and incorporating sensory zoning, a site can cater to a wide array of sensory needs and preferences, balancing priorities while maintaining alignment with the intended uses of the site.

4.7.3. Nature Based Interventions

This study illuminated the positive effects of providing access to nature for the neurodiverse community, encompassing multi-sensory nature experiences, biophilic design, and materiality. The concept of incorporating nature-based approaches emerged from a synthesis of study findings and relevant theories, including Wilson's concept of Biophilia, Ulrich's Stress Reduction Theory, the Kaplans' Attention Restoration Theory, the use of "Soft Fascinators", along with the evolutionary aspects of the Prospect-Refuge Theory.

Additionally, existing field-specific guidelines from the literature review [37,38,44] helped to inform the adoption of this approach.

Observations were made in this study regarding the perceived therapeutic and calming impacts of nature-based elements, including natural lighting, greenery, wildlife, and the presence of water, on the sensory systems of neuro-atypical individuals. Participants revealed a strong affinity for water as sensory support, particularly in terms of soundscapes as an ambient noise buffer. The study also suggested the potential detrimental effects of excessive human intervention, like hardscapes, artificial materials, and anthropophonic noise, as expressed by a substantial portion of the participants. These findings support the utilization of nature-based interventions and the application of established theories, such as the Attention Restoration Theory and Biophilia, to effectively contribute to outdoor environments that accommodate atypical sensory requirements.

The findings do not indicate any conflicts between designing spaces that cater to the sensory needs of neurodivergent individuals and simultaneously the goals of addressing critical environmental issues through nature-based solutions. This includes climate mitigation, water conservation, ecological principles, and regenerative design. Rather, the potential for mutually beneficial relationships and the integration of these concepts is an exciting prospect, fostering a harmonious approach between sensory support and larger systemic objectives.

4.7.4. Co-Design

Participants strongly emphasized the significance of including neurodiverse user groups, associated community members, and experts in the site planning and design of public and community spaces. This may include, but is not limited to, incorporating perspectives from those with lived experiences in neurodiversity, hiring neuro-atypical designers, collaborating with community groups, and involving other experts like occupational therapists who specialize in sensory integration.

These suggestions align with the pre-existing concept of co-design, attributed to esteemed scholars C. K. Prahalad and Venkat Ramaswamy, which originated from design methodologies cultivated in Scandinavia during the 1970s. According to Steen et al. [53] this collaborative approach encompasses participatory, co-creation, and open design processes, underscoring the importance of valuing users as experts in their own lived experiences. Successful execution of co-design initiatives relies on effective facilitation techniques [53] like community design charrettes and storyboards.

4.7.5. SREF Concluding Remarks

The primary objective of the Sensory Responsive Environments Framework is to provide a flexible, non-prescriptive design approach that can aid designers in envisioning potential multi-sensorial barriers that could restrict intended site uses for neurodiverse user groups and determining which design interventions can better serve and support atypical sensory requirements to access the site, while maintaining enough adaptability to respond to site specific contexts, evolving research, and design trends.

The essence of this framework lies in placing marginalized and often overlooked divergent user groups at the center of the design process. Further, the framework pinpoints three key areas that interact in an iterative process to guide sensory-responsive environments, as informed by this study: DSFM, sensory zoning, and nature-based approaches.

4.8. Study Limitations

Acknowledging limitations is essential for maintaining integrity and transparency in research. This study acknowledges limitations, including the challenges posed by undiagnosed or misdiagnosed conditions. Sample bias was a concern, particularly due to misdiagnoses and missed diagnoses among adult women—potentially excluding a large percentage of the target focal groups. Participants' lack of specific terminology may have hindered the full expression of their experiences. Further, the study's primary conduct in Colorado and the lack of systematic tracking of racial and ethnic identities, socioeconomic status, and political affiliations limited its generalizability and analysis of demographic impacts. The restricted participation due to IRB exemptions excluding children and those unable to consent further narrowed the study's scope. It focused on sensory experiences in outdoor spaces, possibly overlooking other aspects of built environments. Further, the findings, while supplementary, are not replacements for specialized medical interventions and may not fully address the needs of groups requiring specific types of support. Despite these limitations, the study provided insights highlighting the need for broader research and innovative design interventions to support and serve atypical sensory needs in built environments.

5. Conclusions: Working Hypothesis

In conclusion, this qualitative study utilized semi-structured interviews with thirty-one participants who have lived experience with neurodivergence and sensory sensitivities, specifically focusing on ADHD, autism, and dyslexia from firsthand, secondhand, and professional perspectives. Through a thematic narrative analysis approach, the research revealed perceived relationships between designed outdoor environments and sensory sensitivities in these user groups, encompassing a ground-up approach to knowledge generation.

The findings identified multiple emergent themes and sub-thematic patterns, highlighting connections between designed elements of outdoor environments and the sensory experiences of neurodivergent individuals. Emergent themes included individual and personal factors, sensory affordances, benefits of outdoor environments, ambient environmental factors, materiality, spatial design, navigating environments, pedestrian-centric transportation, sensorimotor movement, safety, refuge, human settlement types, social environments, and accessibility plus inclusion.

The study highlighted many perceived barriers encountered by dyslexic, autistic, and ADHD individuals with sensory sensitivities in designed landscapes, emphasizing issues with anthropogenic sensory sources like noise pollution and artificial lighting. Other challenges that surfaced included, but were not limited to, navigating environments, vehicle-centric transportation systems, limited sensory refuges in overstimulating environments, and a lack of both options and accessible places for a range of ages and divergent body types.

Many recommended strategies also emerged from this study, through the voices of the neurodiverse community and their allies. These included nature-based design approaches like biophilic design, opportunities for multi-generational sensorimotor engagement, improved wayfinding, prioritizing pedestrian access, and incorporating sensory refuges adjacent to or within overstimulating environments for self-regulation, among others.

In the context of this study, participants expressed a desire for representation within the design process and advocated for outdoor built environments that specifically cater to atypical sensory needs. Whether it's a sensory responsive park within a city or a designated neuro-inclusive trail that considers sensory sensitivities within a broader active transportation system, the call for sensory responsive design approaches aimed at fostering a sense of belonging, welcoming, and recognition strongly resonated. The emphasis was on enabling inclusivity through the diversification of the landscapes themselves, i.e., for designed environments to mirror the diversity of the communities they serve. Questions also arise about the insights that may be uncovered regarding human experiences in designed and built environments through the heightened lenses of those experiencing sensory sensitivities, which may otherwise go unnoticed. These sensitivities could serve as a canary in the coal mine, signaling subtler aspects of our interactions with our surroundings.

Recognizing that outdoor environments are layered, interconnected, dynamic, and living, and understanding their intended uses and existing conditions—including multi-sensory qualities—while applying the Sensory Responsive Environments Framework in the design process presents a versatile strategy for supporting individuals with sensory sensitivities in the planning and design of these environments.

Inspired by Starblade, who reminds us to look on the brighter side of life, and to whom this study is dedicated, designers and readers like you are encouraged to embrace a forward-thinking outlook and remain patient in the pursuit of understanding, acceptance, and inclusion, recognizing that impactful change often unfolds through a series of small steps. Supporting and learning from the neurodiverse community holds potential for various environmental benefits for not only those in the margins, but also those falling in between. Much like a compass pointing the way, neurodiversity directs us toward a responsive landscape that is empathetic, balanced, and attuned to inherently human multi-sensory experiences, offering universal benefits.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land13050636/s1, File S1: IRB Certification; File S2: Interview Protocol.

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Dedication: This study is dedicated to honoring the life of Matthew Paul Finnigan, AKA Starblade, a queer E2 autistic individual who aimed to uncover patterns linking biological and environmental factors, as well as personal growth, to help alleviate challenges faced by autistic individuals.

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Article

Visual Perception Optimization of Residential Landscape Spaces in Cold Regions Using Virtual Reality and Machine Learning

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Abstract: The visual perception of landscape spaces between residences in cold regions is important for public health. To compensate for the existing research ignoring the cold snow season's influence, this study selected two types of outdoor landscape space environments in non-snow and snow seasons as research objects. An eye tracker combined with a semantic differential (SD) questionnaire was used to verify the feasibility of the application of virtual reality technology, screen out the gaze characteristics in the landscape space, and reveal the design factors related to landscape visual perception. In the snow season, the spatial aspect ratio (SAR), building elevation saturation (BS), and grass proportion in the field of view (GP) showed strong correlations with the landscape visual perception scores (W). In the non-snow season, in addition to the above three factors, the roof height difference (RHD), tall-tree height (TTH), and hue contrast (HC) also markedly influenced W. The effects of factors on W were revealed in immersive virtual environment (IVE) orthogonal experiments, and the genetic algorithm (GA) and k-nearest neighbor algorithm (KNN) were combined to optimize the environmental factors. The optimized threshold ranges in the non-snow season environment were SAR: 1.82–2.15, RHD: 10.81–20.09 m, BS: 48.53–61.01, TTH: 14.18–18.29 m, GP: 0.12–0.15, and HC: 18.64–26.83. In the snow season environment, the optimized threshold ranges were SAR: 2.22–2.54, BS: 68.47–82.34, and GP: 0.1–0.14.

Keywords: visual perception optimization; residential landscape space; immersive virtual environment; cold regions; machine learning

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1. Introduction

The optimal design of inter-house landscape spaces in urban residential areas is conducive to the promotion of the high-quality development of urban environments [1]. Existing studies have shown that leisure activities in landscape spaces are beneficial to physical and mental health [2,3]. People are more dependent on familiar landscape spaces in residential areas, and their activities are mostly maintained in residential landscape areas [4]. These spaces play a vital role in people's behavioral activities and psychological recovery [5]. Many studies on public health have demonstrated that the visual perception of people exposed to different environments is significantly different [5–7]. Consequently, it is imperative to study the factors that affect visual perception in specific environments.

Kaplan's attention restoration theory shows that positive environmental perceptions can provide a buffering effect between daily stressors and mental stress [8]. Several studies have indicated that changes in building roof contours, façade decorations, and building height have an impact on a user's potential to have a restorative experience [9]. In recent years, the field of visual perception has attracted significant attention. More than 80% of information received by humans comes from the visual system [10]. The elements and attributes of a landscape environment can affect people's psychology and physiology, and extracting and optimizing environmental factors can effectively improve health [11–14]. Researchers have conducted a significant amount of research on the effect of landscape environments on visual perception. In the research field of visual perception, most of the existing literature focuses only on the effect of light environment indicators (illuminance, daylight uniformity) on people's visual perception and physical and mental health [15,16], but visual comfort includes not only a suitable light environment but also other visual perception factors, such as aesthetic preference. Owing to limitations in technology and equipment, research on the visual evaluation of other factors in the architectural visual environment, such as geometry, material, and color, is limited [16]. Brain responses acquire information through thoughts, experiences, and senses [17]. Environmental assessment is usually carried out by defining people's different visual perception evaluations. Qualitative analyses in this context have typically employed research methods including questionnaires [18], self-report scales [19], group discussions, and interviews [20]. Rogge et al. used the "Likert scale" and "factor analysis" for visual evaluation to obtain users' emotional feelings and reveal aesthetic preferences [21]. Zhang et al. investigated the correlation between street view perception and emotions among college students [22]. Existing studies have shown that there is a strong correlation between visual perception and landscape environment evaluation, and that the environmental information received by human eyes can affect the evaluation of the environment. Recent studies have explored the relationship between landscape environments and physical health [23]. However, there is a lack of refined research on specific leisure scenarios in residential landscape areas. The factors and mechanisms that influence the perception of landscape environmental quality, specifically during non-snow and snow seasons in cold regions, remain insufficiently explored.

From the perspective of the existing literature, traditional research methods such as questionnaires and a combination of scales and interviews are time-consuming, laborious, and easily affected by the investigator's subjective feelings. Gibson's theory of visual perception holds that an object's background constitutes the features of the visual world [24], so it is not accurate to use static photographic visualizations in research. In past studies, in combination with eye tracker experiments, fixation count, fixation duration, and pupil diameter have been used to reflect people's attention to spatial scene elements [25]. Heat maps (to determine the attraction of elements), gaze maps (to indicate the sequence of gazes), and areas of interest (AOIs) can be obtained in eye tracker experiments. These methods are also used in the study of emotional gaze characteristics [26]. Compared with photo tests, virtual reality (VR) experiments are closer to the physical environment in terms of mental and physical reactions and can better awaken participants' emotions [27]. Johnson et al. highlighted the extensive utilization of VR in the design and construction of built environments, emphasizing the need for enhanced research on pedestrian perception through the integration of VR [28]. Luo et al. used VR to simulate the visual perception of people sitting in a park pavilion to assess their preference and mental recovery [29]. To obtain better results, some studies have used eye-tracking technology to explore the influence of indoor and outdoor environments on pedestrian gaze. However, this is limited to arbitrarily changing the visual environment according to the influencing factors in real scenes. Despite the gradual integration of VR technology into the study of visual perception, visual perception research combining VR with an eye tracker for parameter modeling has not yet been conducted.

The k-nearest neighbor algorithm (KNN) is a nonparametric classification method widely used in the fields of computer science and behavioral science. It classifies data using the nearest or adjacent training samples in a given region and calculates the k-nearest neighbor data for a given input value [30]. In the field of architecture, KNN is currently applied to urban lighting design [31], building energy prediction [32], and building thermal comfort performance optimization [33]. Tsalera used a KNN to detect, analyze, and classify urban environmental noise [34]. Genetic algorithms (GAs) combined with simulations are widely used to optimize building space environments. Zhang proposed a method that combined building environment information with a genetic algorithm to optimize the layout of a virtual environment [35]. Awada and Srour used a genetic algorithm as an optimization tool to simulate building renovation schemes and obtained an optimal renovation scheme based on the relationship between indoor environmental quality and occupant satisfaction [36]. Estacio et al. adopted a simulation model combined with a genetic algorithm to obtain an optimal tree distribution strategy under a pedestrian comfort level, thereby proving the feasibility of this optimization method [37]. Many studies have used machine learning and genetic algorithm tools to evaluate and optimize built environments. However, a notable gap in research on the relationship between various elements and visual perception in the landscape spaces of urban houses remains. Additionally, research on the evaluation and prediction of urban residential landscape visual perceptions is relatively underdeveloped. Although some studies have proven that landscape visual perception can affect people's satisfaction evaluations, research on the range of environmental factors influencing leisure landscape spaces using machine learning and genetic algorithms is still insufficient.

This study focused on inter-house landscape spaces in cold regions. The study was conducted in the inter-house landscape spaces of four residential neighborhoods in Harbin City. Tobii Pro Glasses 2 was used to collect eye movement indexes, and a semantic differential (SD) questionnaire was used to collect the visual perception attributes of the subjects. The study combined eye movement metrics validation with the HTC VIVE PRO EYE device and orthogonal experiments using the VR device.

This paper aims to focus on the three following issues.

- This research will reveal the correlation of inter-house landscape design factors with the landscape visual perception scores (W).
- In non-snow and snow seasons, the influence of the landscape design factors on inter-house landscape visual perception scores (W) will be illustrated in this paper.
- By GA combined with KNN, the thresholds of inter-house landscape factors are calculated, and the landscape optimization design method will be shown.

2. Materials and Methods

As shown in Figure 1, the research method was divided into three parts. First, the influencing factors were extracted. Through the eye movement pre-experiment and SD questionnaire, the factors and attributes that affect visual perception in the landscape environment in the non-snow and snow seasons were extracted and verified using the VR eye movement experiment. The second part comprised the construction and analysis of the VR scene model. These factors were used as independent variables to establish immersive VR orthogonal experiments, and a visual perception evaluation under different combinations of factors was obtained. Correlation analysis and data fitting revealed the influence of landscape environmental design factors on visual perception. The third part was the data calculation and model optimization, which used the environmental factors that have a great impact on the landscape visual perception score to build the dataset and train the KNN prediction model. GA was used to optimize the KNN, and the value and threshold range of environmental factors under the evaluation of residents' optimal landscape visual perception based on visual perception were obtained in both the non-snow season and snow season environments in cold regions.

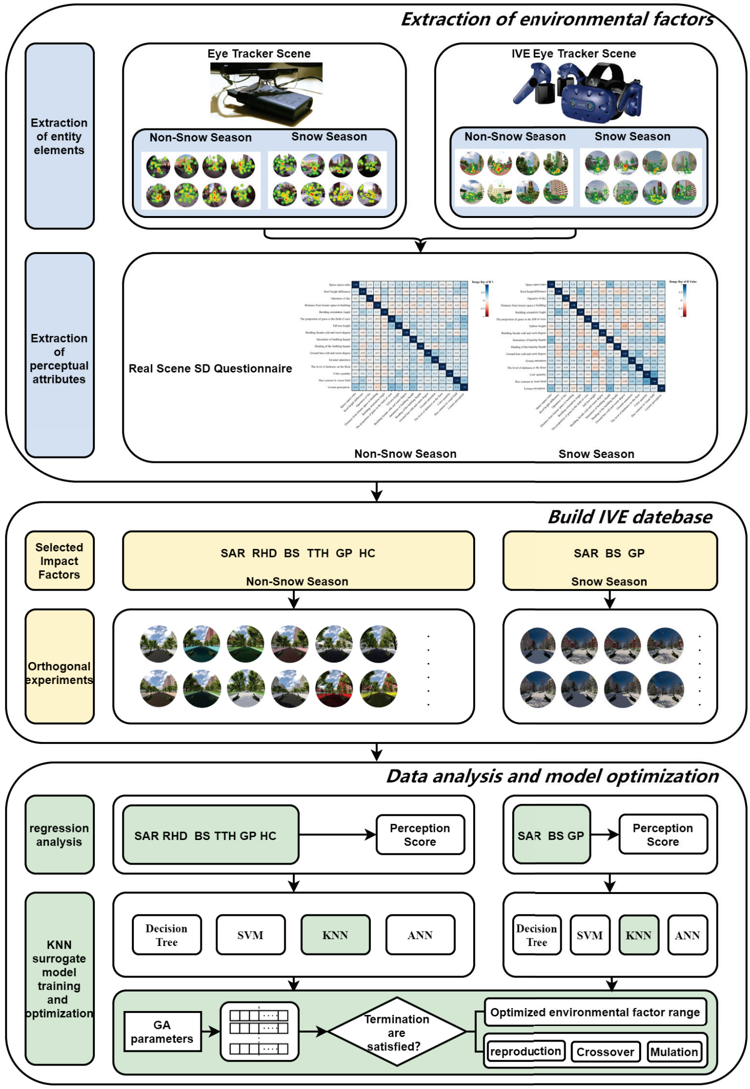
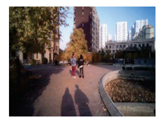
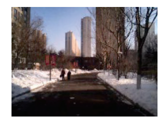


Figure 1. Workflow of the experiment and research procedure (SVM refers to support vector machine, KNN refers to k-nearest neighbor, and ANN refers to artificial neural network. The colored boxes in the figure do not have a clear meaning; they are just for the beauty of the picture).

2.1. Study Area

This study focuses on the inter-house landscape spaces in urban residential areas in cold regions. To explore the influencing factors of specific scenes of landscape space in the snow and non-snow seasons in detail, this study set the landscape's leisure scenario as walking through residential areas. The investigation specifically focused on the landscape space between houses in four typical cold region settlements in the snow and non-snow seasons. SD questionnaires and eye movement experiments were conducted in these four outdoor landscape spaces. Actual interviews with the experimenters were also conducted after experiments as additional information. In addition, a VR scenario was validated using the proposed method. The details of the outdoor landscape spaces in the four urban settlements in cold regions are shown in Table 1.

Table 1. Inter-house landscape spaces in survey (the pictures in the table below were taken in real life and are only used to illustrate the research location, so they were not matched in terms of composition).

Case	A	B	C	D
Construction time	1990	2000	2013	2016
Floor area ratio	2.5	2.1	2.1	2.5
Green space ratio	24%	20%	30%	30%
Live photos (non-snow season)				
Live photos (snow season)				

2.2. *SD Questionnaire*

2.2.1. SD Questionnaire Focus

In this experiment, an SD questionnaire was used to screen the nature of the spatial elements that affect visual perception in landscape spaces. Visual perception attributes were divided into color, geometry, and texture attributes. The HSV (hue, saturation, and brightness) system, number of colors, and color contrast (HC) in the field of view were selected as the color attributes. Geometric attributes included the spatial aspect ratio (SAR), building roof height difference (RHD, the difference between the heights of the lowest and highest residential buildings), sky openness, distance from leisure landscape spaces to residential buildings, building orientation angle, proportion of grass in the field of view (GP), and tall-tree height (TTH). Given the prolonged snow season in cold regions, the attributes of the texture used for building façades and the ground (e.g., bare soil, dirt and pavements where people walk) exhibit minimal seasonal variation, and anti-slip and low-reflectivity materials are widely used. Consequently, texture attributes such as reflectance and refractive index were not considered in this study.

2.2.2. SD Questionnaire Settings

The questionnaire was set up according to the SD method to evaluate the 15 factors of visual perception in leisure landscape spaces between residential buildings that were collected (Table 2). According to the setting requirements of the semantic difference table, the survey was divided into five levels, from left to right: very, generally, neutral, generally, and very, corresponding to 1, 2, 3, 4, and 5 points, respectively. Details of the SD questionnaire can be found in the Supplementary Information. In addition, the landscape visual perception score (W) for each scene was also obtained from one question in the SD questionnaire. The landscape visual perception score (W) refers to the individual's satisfaction with the landscape of the space.

Table 2. Adjective pairs in SD questionnaire.

Number	Factors	Adjective Pairs
1	Space aspect ratio	Narrow–wide
2	Roof height difference	Low–high
3	Openness of sky	Small–big

Table 2. *Cont.*

Number	Factors	Adjective Pairs
4	Distance from leisure landscape space to building	Near–far
5	Building orientation angle	Low–high
6	The proportion of grass in the field of view	Low–high
7	The height of tall trees	Low–high
8	Color of buildings—H	Cold–warm
9	Color of buildings—S	Low–high
10	Color of buildings—V	Darkness–brightness
11	Color of ground—H	Cold–warm
12	Color of ground—S	Low–high
13	Color of ground—V	Darkness–brightness
14	Color quantity	Little–much
15	Hue contrast in visual field	Small–large

	Very	Generally	Neutral	Generally	Very	
Negative	1	2	3	4	5	Positive

2.2.3. Participants of the SD Questionnaire Survey

Each participant assessed their current residential outdoor leisure landscape space (one of the four above) according to the SD questionnaire. In the non-snow season, SD questionnaires were distributed to 940 urban outdoor leisure participants in four different cold regions, including 520 males and 420 females, and 663 questionnaires were returned, with a sample effectiveness rate of 70.5%. The distribution of the number of responses was A: 165 (85 males, 80 females); B: 160 (82 males, 78 females; C: 170 (83 males, 87 females); D: 168 (85 males, 83 females). The participants ranged in age from 18 to 56 years, with a mean age of 43.7 years. During the snow season, 965 questionnaires were distributed to urban outdoor leisure participants in four different cold regions, including 530 males and 435 females, and 693 questionnaires were returned, with a sample effectiveness rate of 71.8%. The distribution of the number of responses was A: 170 (86 males, 84 females); B: 175 (85 males, 90 females); C: 172 (84 males, 88 females; D: 176 (88 males, 88 females). The ages ranged between 18 and 58, with a mean age of 40.3.

2.3. Eye Tracker

2.3.1. Real Scene Eye Tracker

Among the existing studies on the visual perception of the landscape environment, there is some research on the visual gaze characteristics of different hospital staff in outdoor leisure landscape spaces [25], which provides a foundation for the research of this paper. However, the visual attention characteristics of community residents in outdoor landscape environments are still unclear, and whether there are differences in visual attention during the snow and non-snow seasons in cold regions still needs to be discussed. Therefore, it is necessary to analyze the physical elements in the space during the snow and non-snow seasons from the perspective of community residents, which can be completed with the help of an eye tracker.

According to the theory of depth perception, the three-dimensional space seen by pedestrian eyes is lost in the retina, and the perception of three-dimensional space is realized through binocular vision, starting with form perception [38]. In this study, the Tobii professional laboratory platform was used to map eye movement data in a scene video; the scene video was recorded by Tobii Pro Glasses 2 (Tobii, Stockholm, Sweden), and its image is consistent with the computer screen image. Screen images were divided into 10 AOIs: buildings, ground (e.g., bare soil, dirt and pavements where people walk), sky, tall trees, lawns, seats, sports facilities, artificial landscapes, pedestrians, and cars.

The indicators used in the study to measure participants' focus on the areas of interest included the number of fixation points (NF), number of visits (NV), total fixation duration

(TFD), total glance duration (TGD), proportions of fixation time (PFD), and proportions of glance duration (PGD); these indicators fall into four broad categories, the meaning of which has been interpreted by existing research [39–42].

The purpose of the eye-tracking experiment was to find the different visual attention rules of residents walking in the snow and non-snow seasons and to screen the physical elements in the landscape space under the two environments. This experiment required participants to wear a pair of Tobii Pro Glasses 2 (firmware version1.25.6-citronkola). The purpose was to record scene information, eye movement video, and other data streams (pupil size, number of saccades, gyroscope, accelerometer, and TTL input). Data segments can be annotated manually or using user-provided event classification algorithms [39]. Figure 2 shows the eye movement images of the subjects when they were walking between houses in the snow and non-snow seasons.

The study met the minimum criteria for experiments involving eye trackers [40,41]. We used the Tobii Pro Glasses 2, which is a widely used eye tracker that has 4 eye cameras (2 per eye) and 12 illuminators (6 per eye), which are integrated into the frame of the glasses below and above the eyes [42]. Eye movements were recorded at a sample rate of 50 Hz [42]. The participants' head movement was not restricted. Eye positions were recorded for both eyes. The experiments were conducted at 2–4 p.m. on sunny days in the snow season and non-snow season, the experiment sites were outdoor landscape spaces between houses in cold regions, the light source was soft sunlight, and the experimental process was as follows: First, the tester calibrated the eye tracker; the calibration process was provided by the eye tracker manufacturer. Before the formal experiment, the tester introduced the experimental task to the subjects and debugged the experimental equipment. Second, the subject wore an eye-tracking device, and the tester helped the subject correct the fixation point. Finally, the tester started timing and the experiment was officially initiated. When a two-minute walk was completed, the recording ended. The details are shown in Figure 2f. All participants were instructed to walk as they would in their daily lives during the experiment; this is also consistent with existing minimum standards.

The experimental sites were four residential landscape spaces located in the cold region of Harbin, China. These selected communities represented a range of residential areas within Harbin. Experiments were conducted in both snow and non-snow seasons, with 10 subjects randomly recruited for each space, for a total of 40 subjects and 80 experimental cases. All participants indicated that they voluntarily participated and were informed of the experimental task. The mean age of all subjects was 32.4 years. There were 23 males and 27 females. After removing unusable data with a low sampling rate, 64 cases of effective eye movement data were obtained, with a sample effectiveness rate of 80%.

2.3.2. VR Eye Tracker

Because we needed to conduct orthogonal trials with immersive VR devices during subsequent phases of this study, it was imperative to verify whether the gaze characteristics of residents with head-mounted VR devices were similar to reality when taking recreational walks in the scene. Preliminary verification was deemed essential before proceeding with the VR experiments.

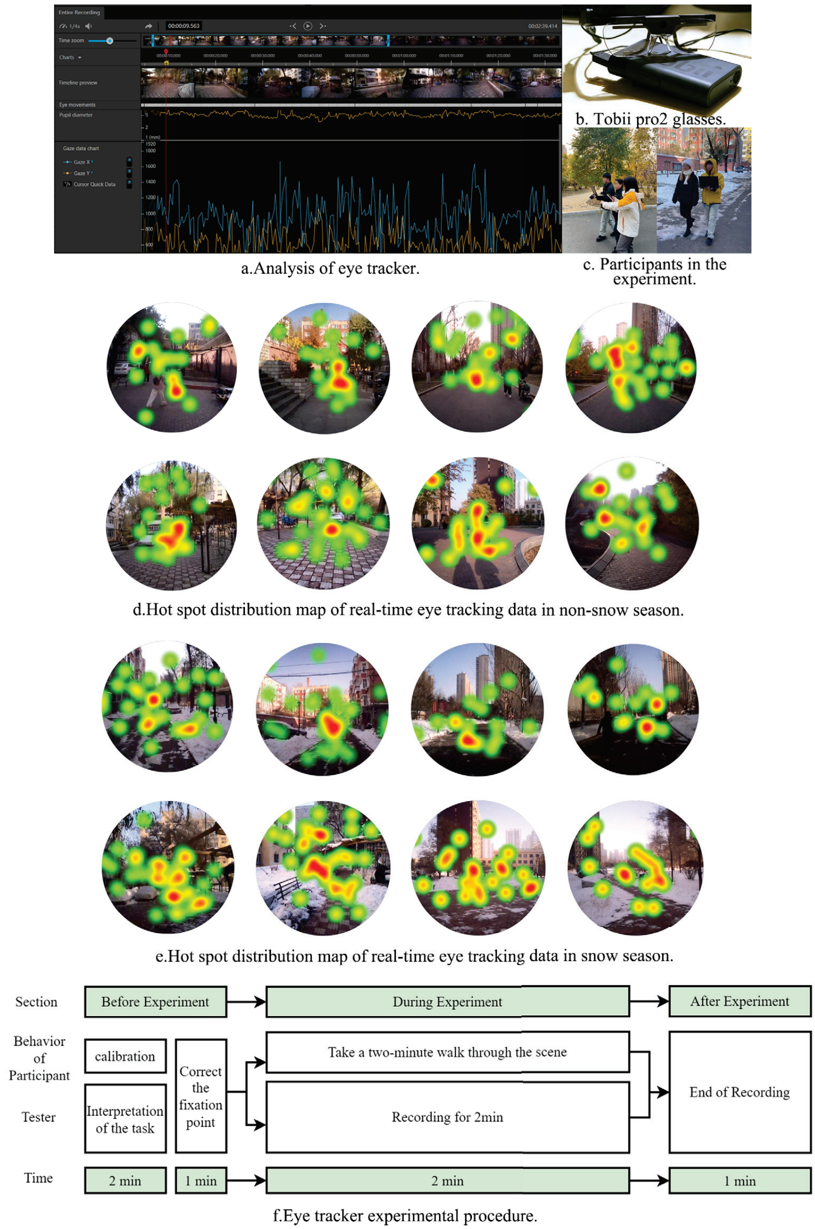


Figure 2. Eye-tracking experience process. (**a**) Analysis of eye tracker; (**b**) Tobii Pro Glasses 2; (**c**) participants in the experiment; (**d**) hot spot distribution map of real-time eye-tracking data in non-snow season; (**e**) hot spot distribution map of real-time eye-tracking data in snow season (Green for points of interest and red for dense points of interest); (**f**) eye tracker experimental procedure.

In this study, the Unity 2019.4.30f1c3 (64-bit) software (accessed date were June and November 2023) platform was used to construct the experimental scene, ensuring the accurate recreation of all elements and attributes to reflect the actual scene. The data needed to build the Unity model included the SketchUp model based on the actual measurement of the site and the related model material. When wearing the VR eye tracker, participants saw a computer-generated 3D environment. Participants wore an HTC VIVE PRO EYE, the gaze data output frequency (binocular) was 120 Hz, and the head movement of the participants was not restricted. The HTC VIVE PRO EYE is equipped with sensors including Steam VR™ tracking, gravity sensors, gyroscopes, interpupil distance sensors, binocular comfort settings (IPD), and Tobii® eye tracking, which allow users to recreate realistic walking behavior in the scene. The HTC VIVE PRO EYE can display images with a binocular resolution of 2880 × 1600, a field of view of 110°, a refresh rate of 90 Hz, and an accuracy of 0.5–1.1°. The calibration process was provided by the eye tracker manufacturer, and the device can record the eye movement behavior data of each subject's eyes, as shown in Figure 3a. The eye movement data recorded in the experiment were processed using the eye movement analysis function on the ErgoLAB platform [43]. The experiment was validated in two ways, the first being the subjects actually walking with the HTC VIVE PRO EYE on their heads, and the second being the subjects sitting still with the device on their heads but using the joysticks to control their walking in order to achieve behavior that was more in line with the subject's eye movements when walking in the real-life environment in which they live. Figure 3c shows a photograph of a subject wearing the HTC VIVE PRO EYE during the test. Figure 3d,e show screenshots of eye movement characteristics recorded when subjects were actually walking between houses during the non-snow season versus the snow season.

The experiment was carried out at 2–4 p.m. on sunny days in the snow season and non-snow season, respectively. The experimental site was an outdoor landscape place in cold regions, and the light source was soft sunlight. The experimental process was the same. A total of 32 subjects were included in this experiment. The experiment was kept the same for snow season and non-snow season subjects. Each of them carried out two sets of actual walking and remote control in the snow season and non-snow season, respectively, and all of them volunteered to participate in the experiment. There were 8 scenes in total (4 sites in 2 seasons), and 8 local residents in each scene carried out the experiment; a total of 128 sets of experiments were performed (8 times 8 times 2, equaling 128).

2.4. Orthogonal Experiment

2.4.1. Orthogonal Experimental Setup

In this study, urban outdoor landscape spaces were considered to be outdoor places for residents to chat, walk, keep fit, and perform other functions. In the non-snow and snow seasons in cold regions, these spaces generally contain buildings, the ground, tall trees, lawns, seats, sports facilities, and artificial landscapes. As shown in Figures 4a and 5a, combined with the case study of outdoor landscape spaces in residential areas in cold regions, the experimental model was constructed based on the prototype of the Fuhua residential area and the Lushang New Town residential area in Harbin, and the parameters were adjusted accordingly.

The study screened six environmental factors with a strong correlation with landscape visual perception scores based on the SD questionnaire as variable parameters for constructing the VR scene, which were the spatial aspect ratio (SAR), roof height difference (RHD), color saturation of buildings (BS), tall-tree height (TTH), proportion of grass in the field view (GP), and color contrast (HC). The specific thresholds are proposed below for the subsequent construction of orthogonal VR experiments, and the thresholds for each variable were set to 6–7 steps in order to facilitate the construction of the experiments, as shown in Tables 3 and 4.

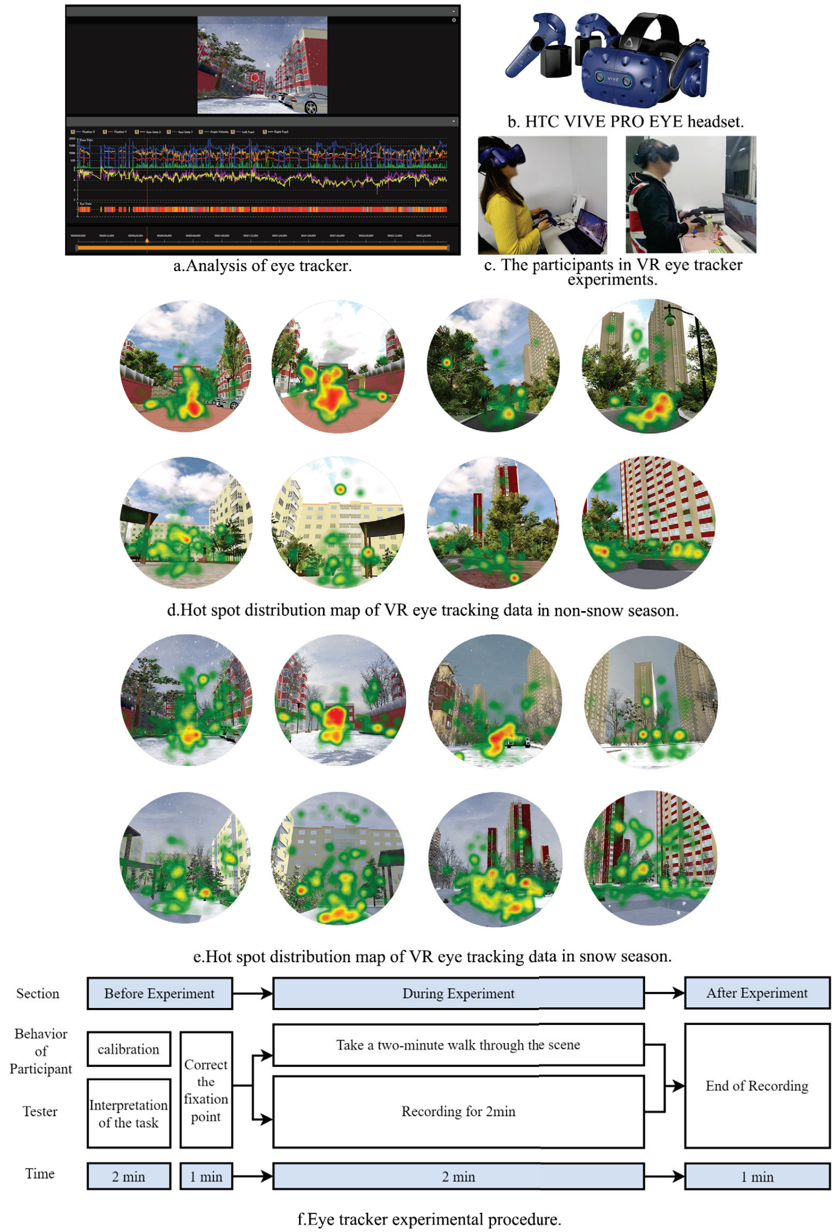
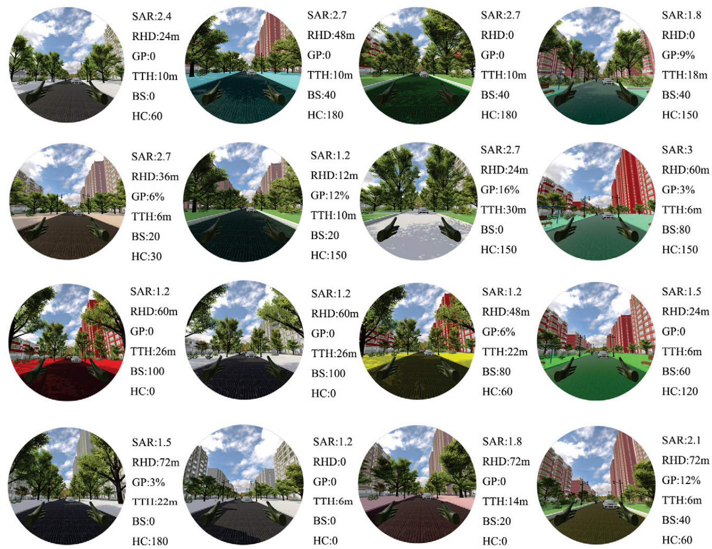
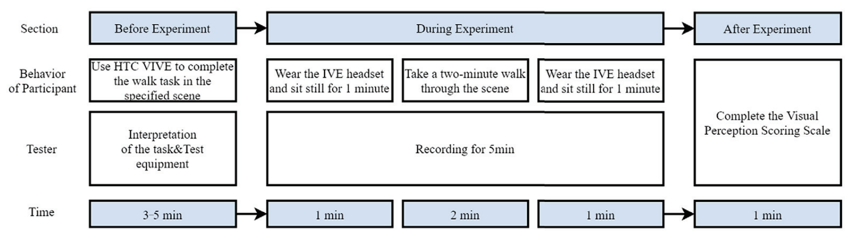


Figure 3. Process of VR eye-tracking experiment. (**a**) Analysis of eye tracker; (**b**) HTC VIVE PRO EYE headset; (**c**) the participants in VR eye tracker experiments; (**d**) hot spot distribution map of VR eye-tracking data in non-snow season; (**e**) hot spot distribution map of VR eye-tracking data in snow season (Green for points of interest and red for dense points of interest); (**f**) eye tracker experimental procedure.



a.Parametric VR scene in orthogonal experiment during the non-snow season.



b.Orthogonal experiment procedure in VR scene.

Figure 4. Orthogonal experiment parameters and procedure using VR scenes in the non-snow season. (**a**) Parametric VR scene in orthogonal experiment during the non-snow season; (**b**) orthogonal experiment procedure in VR scene.

Table 3. Orthogonal experimental parameters in the non-snow season.

Environmental Factors	Orthogonal Experimental Parameters in the Non-Snow Season
Space aspect ratio (SAR)	1.2, 1.5, 1.8, 2.1, 2.4, 2.7, and 3
Roof height difference (RHD)	0 m, 12 m, 24 m, 36 m, 48 m, 60 m, and 72 m
Color saturation of buildings (BS)	0, 20, 40, 60, 80, and 100
Tall-tree height (TTH)	6 m, 10 m, 14 m, 18 m, 22 m, 26 m, and 30 m
The proportion of grass in the field of view (GP)	0, 3%, 6%, 9%, 12%, and 16%
Hue contrast in the visual field (HC)	0, 30°, 60°, 90°, 120°, 150°, and 180°

Table 4. Orthogonal experimental parameters in the snow season.

Environmental Factors	Orthogonal Experimental Parameters in the Snow Season
Space aspect ratio (SAR)	1.2, 1.5, 1.8, 2.1, 2.4, 2.7, and 3
Saturation of buildings (BS)	0, 20, 40, 60, 80, and 100
The proportion of grass in the field of view (GP)	0, 3%, 6%, 9%, 12%, and 16%

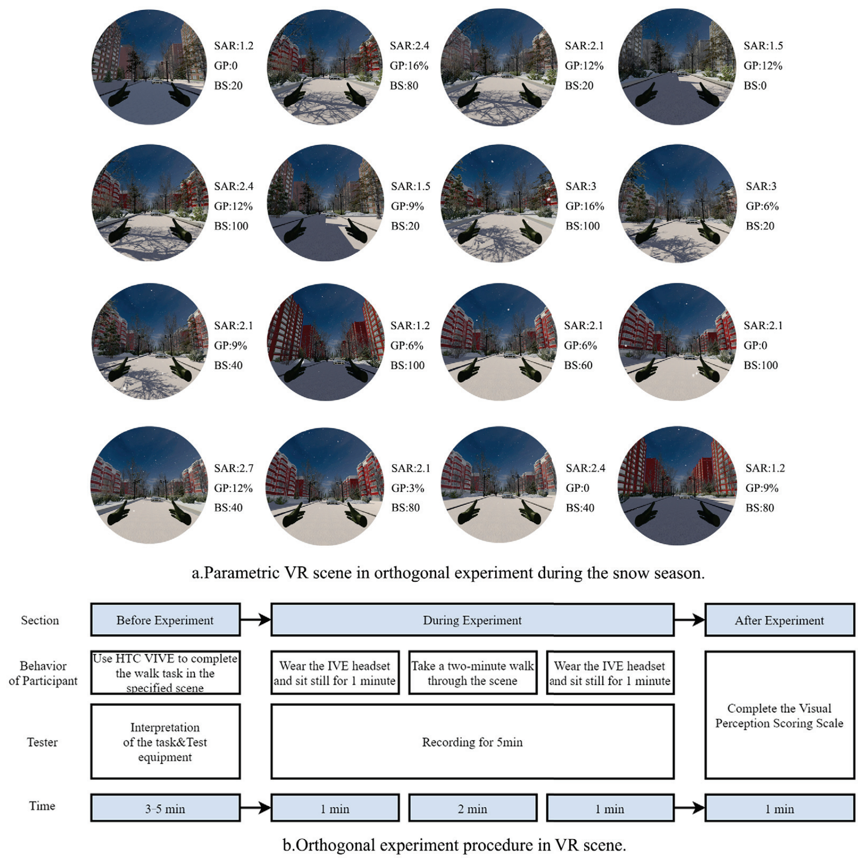


Figure 5. Orthogonal experiment parameters and procedure using VR scenes in the snow season. (**a**) Parametric VR scene in orthogonal experiment during the snow season; (**b**) orthogonal experiment procedure in VR scene.

In the variable setting, the SAR referred to the "D/H" index proposed in *External Space Design* by Ashihara Yoshinobu [44]; it refers to the ratio of the width (D) formed between the two sides of a building to the mean height of the building (H). The object of the study was the residential buildings of Harbin City, which is dominated by multilayer and high-rise buildings, and the building's height being too low is not taken into account here, for the time being. When D/H < 1, the external space provides a sense of urgency; when D/H > 3, the external space has poor enclosure [44]. Therefore, as shown in Tables 3 and 4, the space aspect ratios were set to 1.2, 1.5, 1.8, 2.1, 2.4, 2.7, and 3. In this study, the RHD refers to the height difference between the highest and lowest residential buildings around the landscape spaces; the study targeted the roofs of the buildings closest to the participants. Because the main urban area of Harbin is dominated by multistory and high-rise buildings, and the number of grounds is mostly 6–30 [45], this study set the RHD to 0 m, 12 m, 24 m, 36 m, 48 m, 60 m, and 72 m. Based on the SD questionnaire and actual interviews, it was shown that the proportion of grass in the field of view affects residents' landscape perception, so this study investigated how the percentage of lawns in the field of view impacted the visual perception of the landscape. GP refers to the concept of the green viewing rate [46]; in this study, the ratio of the green pixel value to the total pixels of the lawn in this space was derived by calculating the ratio of the green pixel value to the total pixels of the lawn through the Adobe Photoshop 2022 software (accessed date were

June and November 2023), and the photo data were collected and averaged several times. Some studies have shown that a more appropriate green viewing rate is 24–34% [47]. The GP was set to 0, 3%, 6%, 9%, 12%, and 16%. Most trees in Harbin are 6–30 m. Therefore, in this study, the TTH was set to 6 m, 10 m, 14 m, 18 m, 22 m, 26 m, and 30 m, and the height of trees can be modeled in the Unity 2019.4.30f1c3 (64-bit) software and adjusted according to one's requirements. Saturation is one of the three attributes in the HSV color model; the value range is 0–100. BS refers to the saturation of the color of the main body of the building, which can be set to 6 levels from low to high by the Unity3D software: 0, 20, 40, 60, 80, and 100, respectively. HC refers to the difference between the two main colors in a scene [48]. In this study, it refers to the hue difference between the main building and the ground. The strength of the difference depends on the angle difference on the hue ring, and in this study, it was set to seven levels from low to high at 30° intervals.

An orthogonal experimental design was used in the model design, which is a method of selecting some representative points from the comprehensive experiment according to the orthogonality when conducting the experiment. As shown in Figures 4a and 5a, the orthogonal experimental design of the experimental model through SPSS yielded a total of 49 sets of scenarios and combinations of variables for each of the snow and non-snow seasons, resulting in a total of 98 sets. Only 16 of the 49 scenarios from each of the two environments are shown in Figures 4a and 5a; the parameters for each scenario are labeled. Each participant needed four hours to participate in the experiment. The experiment was spread over 20 days in the non-snow season and 20 days in the snow season.

2.4.2. Orthogonal Experiment Procedure

Before the start of the experiment, all participants were introduced to the task and purpose of the experiment, and signed a formal consent form. There were 40 participants (22 males and 18 females) with an average age of 38.8 years (standard deviation, 3.5). Most participants had no architectural background and were in good health before the experiment. A total of 1960 sets of experiments were completed in the non-snow season and 1960 sets of experiments were completed in the snow season, of which 1685 sets of valid data were available in the non-snow season (85.97% validity) and 1697 sets of valid data were available in the snow season (86.58% validity). Some data were considered invalid due to extreme ratings by some participants (e.g., all choice 1 or all choice 5).

The experiment was conducted in sunny weather during the non-snow and snow seasons. As shown in Figures 4b and 5b, before the experiment, the subjects wore the VR equipment and walked in the scene for 3–5 min to familiarize themselves with the equipment. Subsequently, the experiment officially started, and the subjects first sat for 1 min, then walked normally for 2 min, and finally sat for 1 min. At the end of the experiment, a visual perception rating form was filled out, which consisted of basic information such as gender, age, occupation, and landscape visual perception score of the scene viewed on a scale of 1–5. The study followed the approval process of the Medical Ethics Committee of the host institution, Harbin Institute of Technology (No. HIT-2024003).

2.5. Machine Learning and Genetic Algorithms

2.5.1. Machine Learning

The goal of the visual perception optimization of outdoor landscape environments is to determine the optimal composition of spatial environmental factors and the threshold range of impact factors by adjusting the environmental factors that affect landscape visual perception scores to improve user satisfaction. In this study, classification and regression algorithms were first tested for their ability to learn data features, and the structures of the algorithm models were then compared and optimized to yield refined surrogate patterns. In total, 1685 sets of experimental data were used for training during the non-snow season, and 1697 sets of experimental data were used for training during the snow season. The trained surrogate model could predict the visual perception score of the outdoor landscape environment in a cold region using an environmental factor dataset in both seasons.

Most existing studies on perceptual evaluation have used classification machine learning for predictions [49,50]. Although the data used for machine learning classification methods are discontinuous and are distinguished from traditional linear regression methods, there are currently applications in the field of environmental building research. For example, in a thermal environment, Jing et al. used seven classification scoring evaluation data combined with the gray wolf optimization algorithm and back-propagation neural network, and finally proposed a prediction model for outdoor clothing [51]. In terms of acoustic environments, Jin Yong Jeon and Joo Young Hong conducted a five-category regression prediction of people's perceived soundscape in urban parks, and the accuracy of the prediction using an artificial neural network (ANN) was 84% [52]. In terms of indoor air quality, Kong et al. utilized 3-classification scoring evaluation data combined with multiple machine learning classification algorithms such as gradient boosting machine, ANN, etc., and the gradient boosting machine had the highest accuracy of 60.5%–67.2% [53]. In terms of visual perception evaluation, Berman et al. obtained 7-category scores from subjects on the naturalness of images, and combined these with quadratic discriminant classification algorithms to obtain a prediction method of whether a scene is natural or not [54]. Therefore, this study could also use classification machine learning for visual perception environment prediction in inter-house landscape space. Because the visual perception satisfaction of the landscape environment was evaluated as a score on a 5-point scale, scores were obtained by completing a visual perception rating scale after viewing 49 sets of scene experiments for each of the 2 environments in both the non-snow and snow seasons. In this study, the classification algorithm was selected to predict the categories; in the training process of the surrogate model, the landscape visual perception score was used as the output; and the values of environmental influence factors in the non-snow and snow seasons were used as the input dataset. In this study, the effects of decision tree, support vector machine, KNN, and ANN on the classification calculation methods were compared, and KNN was selected as a suitable surrogate model; the relevant details and mathematical formulae are detailed in the Appendix A.

In this study, the prediction results of four classification algorithms were compared, and the model structure was adjusted according to the fitting effect. The input datasets were 1960 sets of landscape environment-influencing factors in the non-snow and snow seasons, and the output datasets were landscape visual perception scores. Parameters applicable to this study were derived after summarizing based on established studies [49–54]; 70% of the dataset was used for training, 15% for validation, and the remainder for testing. The study was set up in the MATLAB R2022a software classification algorithm. The validation set was the sample set used to tune the hyperparameters of the classifier. The test set was the sample set used only for a performance evaluation of the already-trained classifier.

2.5.2. Genetic Algorithm

The theoretical basis of genetic algorithms is derived from the theory of biological evolution and natural selection. When applied to optimization in the field of artificial intelligence, genetic algorithms can solve complex problems with and without constraints [55]. In the optimization process, the output value can be obtained according to the input value, and the "optimal solution" can be obtained by defining the output mode [56]. In this study, the predicted output value (W) was used as a genetic fitness index to determine the optimal range of environmental parameters for the visual perception of landscape environments. Based on related studies [57,58], the parameters of the GA were set as follows: the population size was 200, the crossover fraction was 0.8, and the migration fraction was 0.2. During the non-snow season, 200 different cases of the SAR, RHD, TTH, BS, GP, and HC were input, and 200 corresponding W values were evaluated to determine the maximum in every generation. During the snow season, 200 different cases of the SAR, GP, and BS were input, and the 200 responding W values were evaluated to find the maximum in every generation. It should be noted that because the GA of MATLAB could only calculate the minimum value, in this study, to obtain the maximum value of W, the optimized target was set as the opposite of W.

3. Results

3.1. Identification of Important Factors Influencing Visual Perception

3.1.1. SD Questionnaire Element Screening

Pearson correlation analysis was conducted between the 15 target variables and the dependent variable (landscape visual perception score) in the non-snow season and the snow season. The results of the Pearson correlation coefficient (r) are shown in Figures 6 and 7. The Pearson correlation coefficient is denoted as r; the range is [−1, 1]. When r is greater than 0.2, it is considered that there is a meaningful correlation between the two variables [59]. If the value is a positive number, it is a positive correlation; if the value is a negative number, it is a negative correlation. The closer the value is to 1, the more relevant it is.

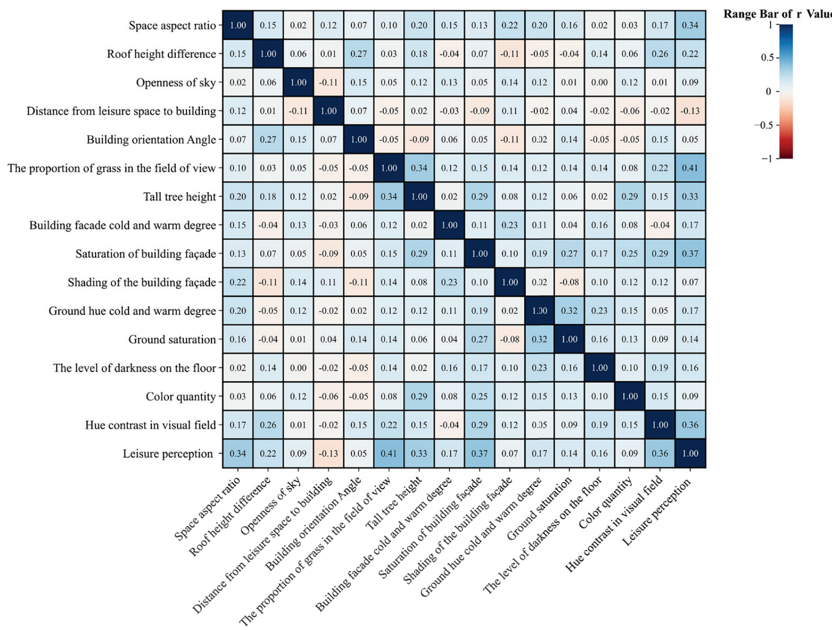


Figure 6. Correlation analysis between the environmental impact factors and landscape visual perception in the non-snow season.

The independent variables in the non-snow season were the spatial aspect ratio (r = 0.34), roof height difference (r = 0.22), proportion of grass in the field of view (r = 0.41), height of tall trees (r = 0.33), building façade saturation (r = 0.37), and color contrast (r = 0.36), which were significantly associated with the dependent variable (landscape visual perception scores). Among the independent variables of the snow season, the SAR (r = 0.38), the proportion of grass in the field of view (r = 0.34), and the saturation of the building façade (r = 0.45) were significantly correlated with the dependent variable (landscape visual perception scores). Therefore, six leisure landscape visual influence factors were selected for the non-snow season and three for the snow season.

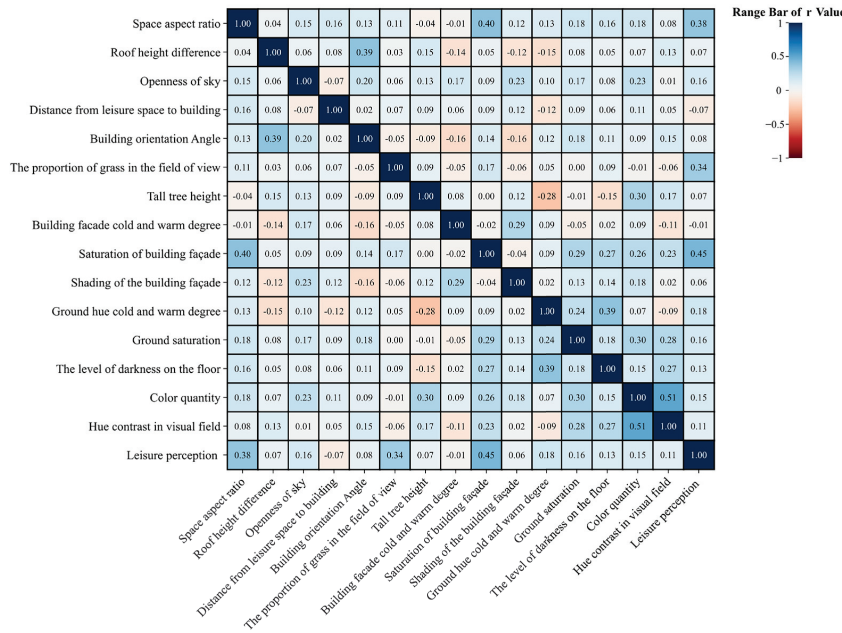


Figure 7. Correlation analysis between the environmental impact factors and landscape visual perception in the snow season.

In the non-snow season, the influence of building saturation in terms of color attributes was higher than that of hue and value, which may be because building saturation can affect residents' emotional and behavioral choices for leisure walking. The hue contrast in the visual field had a greater influence on leisure landscape visual perception than the number of colors, which means that the hue contrast between the two dominant colors in the landscape environment encourages the user to produce more positive emotions. In terms of spatial geometric elements, the selected spatial aspect ratio and roof height difference reflect spatial openness, which will make people capture different amounts of information and then affect the visual experience of the users. In this view, the proportion of grass gave people a different feeling of being green. The height of tall trees influenced users to obtain different degrees of cool feelings in the non-snow season. In the snow season, the influence of building saturation on color attributes was higher than that of hue and value, and whether they were cold and warm hues had little effect, which may be because most building façades in the cold regions were warm colors. Spatial openness under the influence of the SAR on geometric attributes still affected visual perception during the snow season. A greater amount of grass in the field of view was associated with more positive emotions during the snow season.

3.1.2. Eye Tracker Interest Point Screening

The purpose of the eye tracker experiment was to screen out the entity elements that have a great influence on visual perception in the non-snow and snow seasons and to determine the visual attention rules of residents during leisure walking. The data analysis results of the 40 cases of experiments in both the snow and non-snow seasons are as follows.

In the non-snow season, as shown in Figure 8a, the average results for NF and NV were ground > buildings > tall trees > lawn > sky > pedestrians > artificial landscape > seats > sports facilities > cars. In Figure 8b, the average results for TFD and TGD were as follows: ground > buildings > tall trees > lawn > sky > artificial landscape > pedestrians > seats > cars > sports facilities. However, PFD and PGD are shown in Figure 8c as follows:

ground > buildings > tall trees > lawn > sky > artificial landscape > pedestrians > seats > cars > sports facilities.

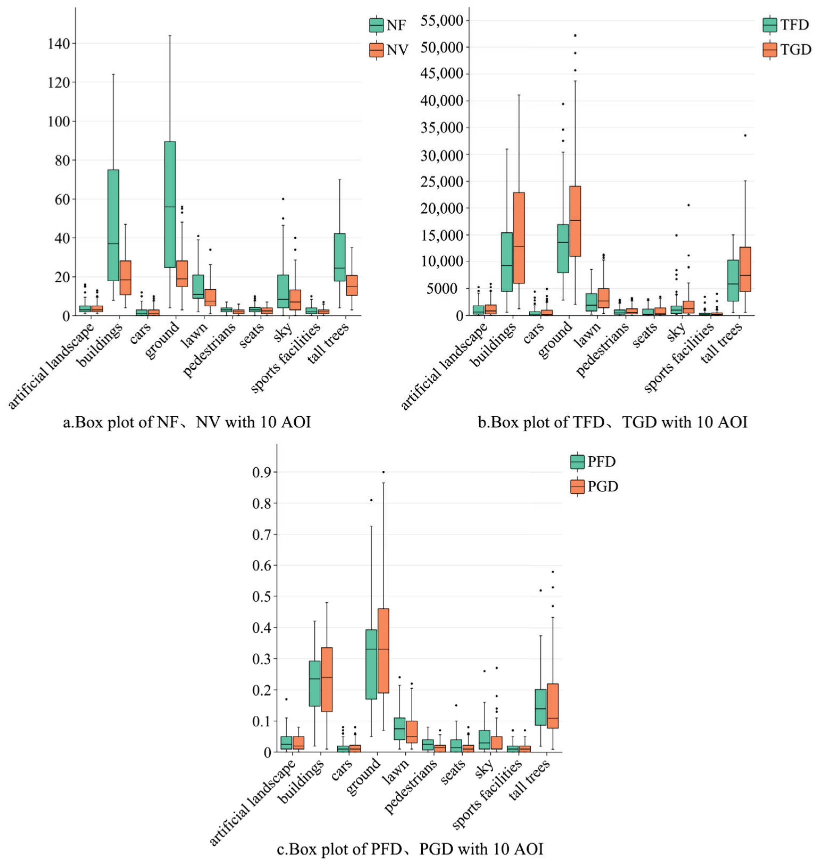


Figure 8. Analysis of leisure gaze features in real scene in non-snow season. (**a**) Box plot of NF and NV with 10 areas of interest; (**b**) box plot of TFD and TGD with 10 areas of interest; (**c**) box plot of PFD and PGD with 10 areas of interest.

In the non-snow season environment, the gaze characteristics of people engaged in leisure walking between houses in cold regions were similar. In the outdoor leisure landscape environment, the attention paid to the ground, buildings, tall trees, and lawns was higher than that paid to seats, cars, and sports facilities, which was consistent with actual walking behavior. Although participants paid moderate attention to the sky, considering that the openness of the sky is affected by buildings and tall trees, this study selected the ground, buildings, tall trees, and lawns as the environmental entity elements affecting visual perception in non-snow season environments.

In the snow season, as shown in Figure 9a, the average results for NF were as follows: ground > tall trees > buildings > lawn > sky > artificial landscape > seats > pedestrians > cars > sports facilities. The average result of NV was ground > buildings > tall trees > lawn > sky > artificial landscape > seats > pedestrians > cars > sports facilities. In Figure 9b, the average results for TFD and TGD were as follows: ground > buildings > tall trees > lawn > sky > artificial landscape > pedestrians > seats > cars > sports facilities. However, PFD and PGD are shown in Figure 9c as follows: ground > buildings > tall trees > lawn > sky > artificial landscape > seats > pedestrians > cars > sports facilities.

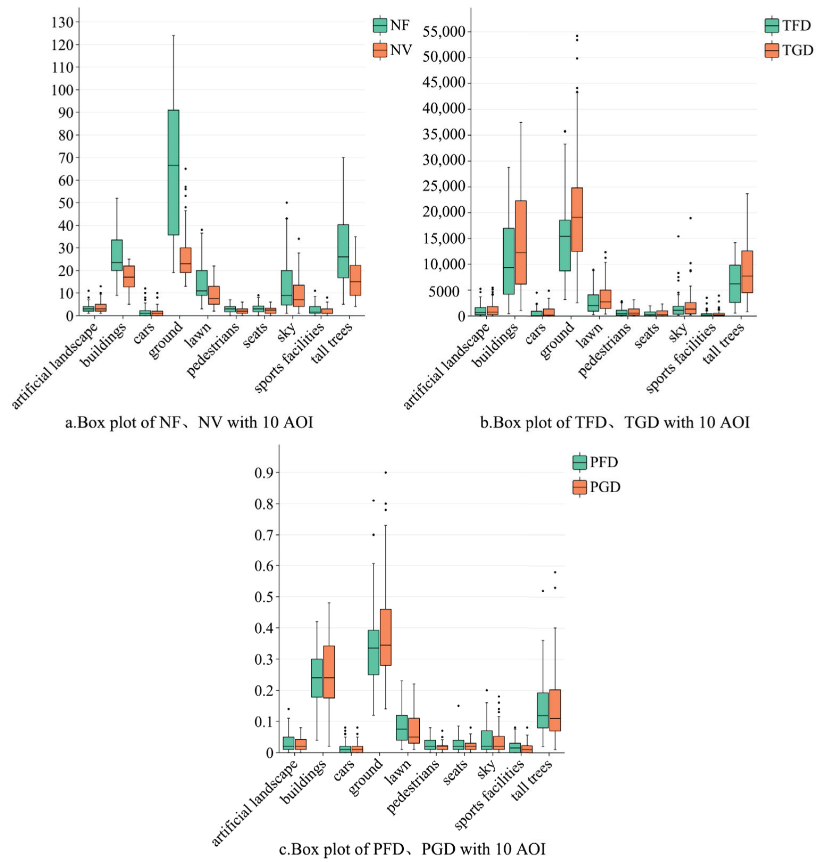


Figure 9. Analysis of leisure gaze features in real scene in snow season. (**a**) Box plot of NF and NV with 10 areas of interest; (**b**) box plot of TFD and TGD with 10 areas of interest; (**c**) box plot of PFD and PGD with 10 areas of interest.

In the snow season environment, the ground, buildings, tall trees, and lawns remained the top four elements of attention when people took leisure walks, while the other six elements were relatively insignificant. Therefore, this study selected the ground, buildings, tall trees, and lawns as environmental entity elements that affect visual perception in the snow season.

3.1.3. VR Eye-Tracking Verification

The purpose of the VR eye-tracking experiment was to verify whether the gaze characteristics of the subjects in an immersive VR scene represented the gaze characteristics of the actual scene. Through the analysis of 32 cases of data in the non-snow season environment, when the participants were walking with the joysticks, as shown in Figure 10a, the average result of NV was buildings > tall trees > ground > sky > lawn > artificial landscape > seats > pedestrians > cars > sports facilities. In Figure 10, the average results for NF, TFD, TGD, PFD, and PGD show a pattern of buildings > ground > tall trees > sky > lawn > artificial landscape > seats > pedestrians > cars > sports facilities. Through the analysis of 32 cases of data during the snow season, as shown in Figure 11a, NF was as follows: buildings > ground > tall trees > lawn > sky > artificial landscape > cars > seats > pedestrians > sports facilities. The average result of NV was buildings > tall trees > ground > sky > lawn > artificial landscape > seats > cars > pedestrians > sports facilities. In Figure 11b,c, from the average results of the TFD, TGD, PFD, and PGD, the top four are the ground, buildings, tall trees, and lawns.

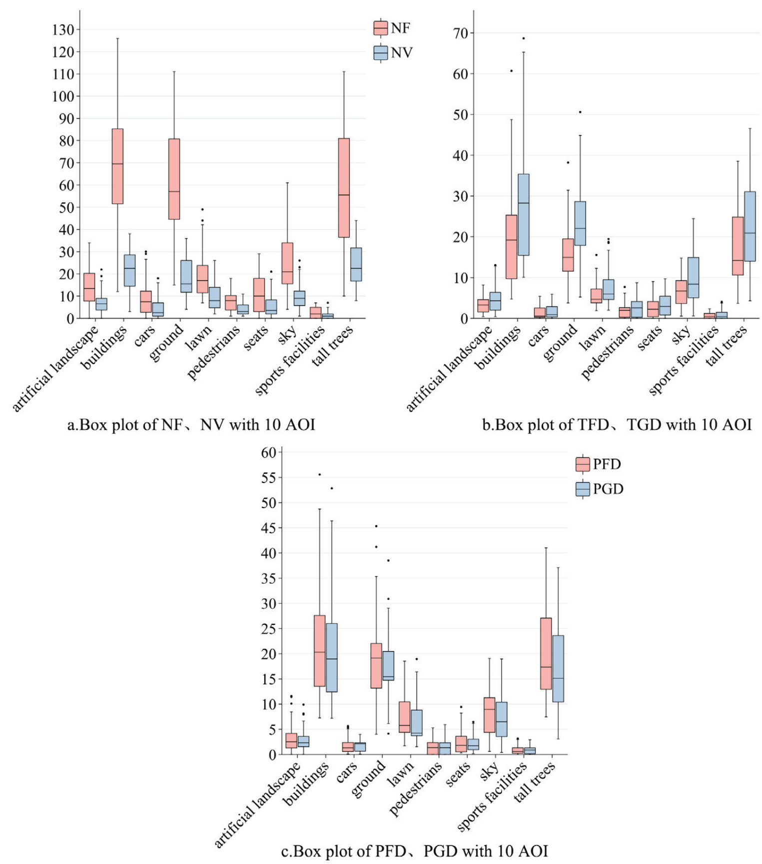


Figure 10. Analysis of gaze analysis of VR scenes using the joysticks in non-snow season. (**a**) Box plot of NF and NV with 10 areas of interest; (**b**) box plot of TFD and TGD with 10 areas of interest; (**c**) box plot of PFD and PGD with 10 areas of interest.

When subjects were actually walking with the HTC VIVE PRO EYE on their heads, in the non-snow season environment, as shown in Figure 12, the average results for NV, NF, TFD, TGD, PFD, and PGD were all as follows: ground > buildings > tall trees > sky > lawn > artificial landscape > seats > pedestrians > cars > sports facilities. In the snow season environment, as shown in Figure 13, the average result of NF was ground > buildings > tall trees > lawns > sky > artificial landscapes > cars > seats > pedestrians > sports facilities. The average result of NV was ground > buildings > tall trees > sky > lawn > artificial landscape > seats > cars > pedestrians > sports facilities. In Figure 13b,c, the top four rankings from the average results of TFD, TGD, PFD, and PGD are ground, buildings, tall trees, and lawn.

It was found that the gaze characteristics of participants leisure walking with the HTC VIVE PRO EYE on their heads in the VR scene were consistent with those in the real scene, which supported that it was feasible to select the ground, buildings, tall trees, and lawns, ranked in the top four, as entity elements in the subsequent orthogonal VR experiments. In addition, from the ordering of the degree of attention of each element, the ordering of the elements for real walking with the head-mounted device is closer to the real situation in Figures 8 and 9, and walking with the head-mounted VR device in a real environment without using joysticks is more realistic than sitting and using joysticks via remote control. Therefore, combining the entity elements selected by the eye tracker experiment with the attributes selected by the SD questionnaire, the six environmental impact factors of landscape visual perception scores that were selected in the non-snow season were the SAR, RHD, GP, TTH, BS, and HC. The three environmental impact factors of landscape visual perception scores in the snow season were the SAR, GP, and BS.

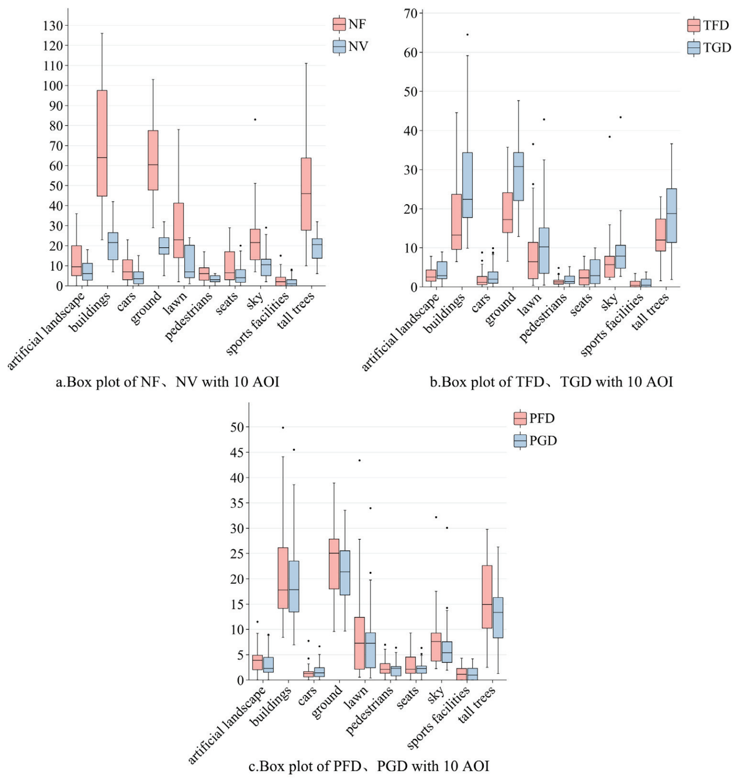


Figure 11. Analysis of gaze analysis of VR scenes using the joysticks in snow season. (**a**) Box plot of NF and NV with 10 areas of interest; (**b**) box plot of TFD and TGD with 10 areas of interest; (**c**) box plot of PFD and PGD with 10 areas of interest.

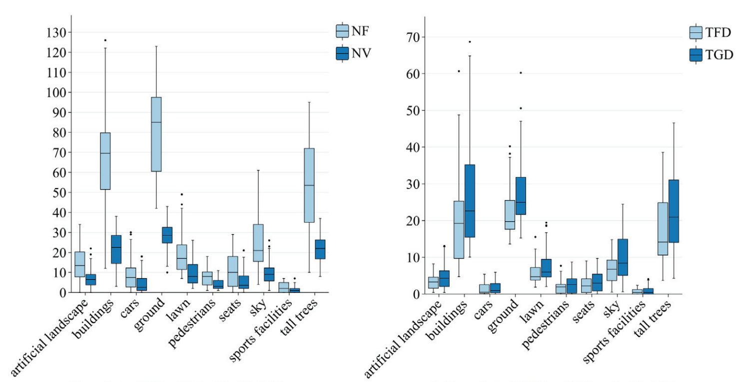
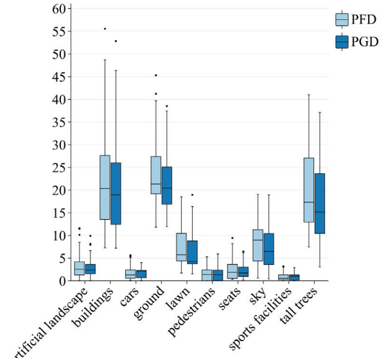
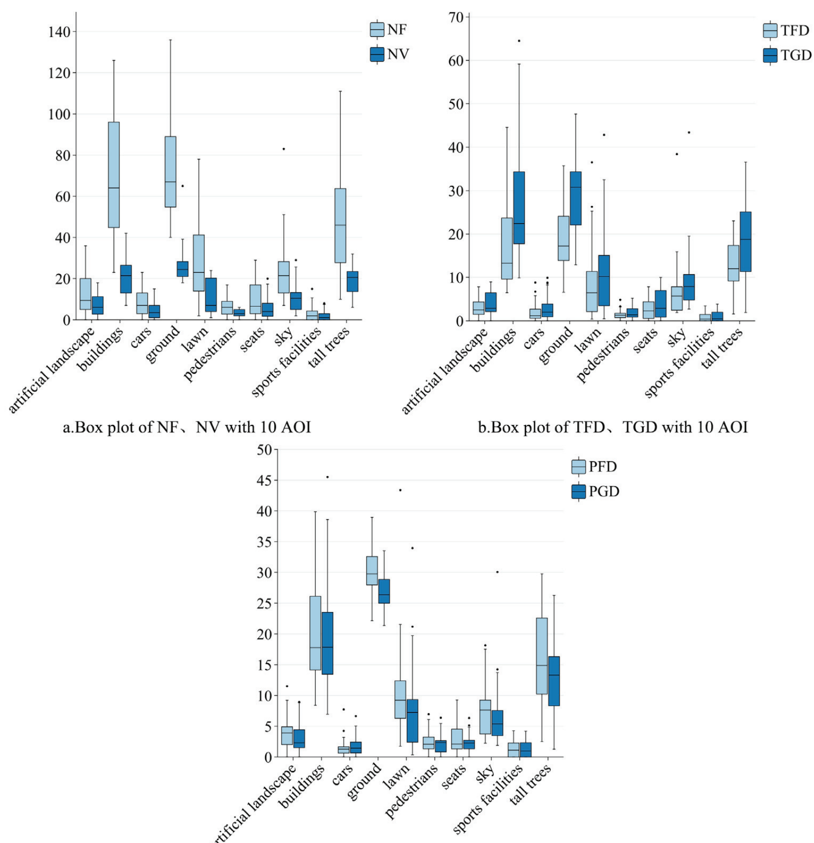


Figure 12. *Cont.*



c.Box plot of PFD、PGD with 10 AOI

Figure 12. Gaze analysis of actual-walking VR scenes without the use of joysticks in non-snow season. (**a**) Box plot of NF and NV with 10 areas of interest; (**b**) box plot of TFD and TGD with 10 areas of interest; (**c**) box plot of PFD and PGD with 10 areas of interest.



a.Box plot of NF、NV with 10 AOI

b.Box plot of TFD、TGD with 10 AOI

c.Box plot of PFD、PGD with 10 AOI

Figure 13. Gaze analysis of actual walking VR scenes without the use of joysticks in snow season. (**a**) Box plot of NF and NV with 10 areas of interest; (**b**) box plot of TFD and TGD with 10 areas of interest; (**c**) box plot of PFD and PGD with 10 areas of interest.

3.2. Influence Mechanism

3.2.1. Influence Mechanism of Environmental Factors in Non-Snow Season

As shown in Figure 14, in the non-snow season environment, according to the correlation analysis, the landscape visual perception score (W) was correlated with the SAR, BS, GP, RHD, TTH, and HC. Since the dependent variable was a rating of 1–5, the correlation was small, and although the correlation results show a small correlation, they reveal a relationship between the independent variable and the dependent variable, which will be further investigated in future studies with a view to obtaining a higher correlation. The range when W is at its maximum value is shown between the vertical dotted lines.

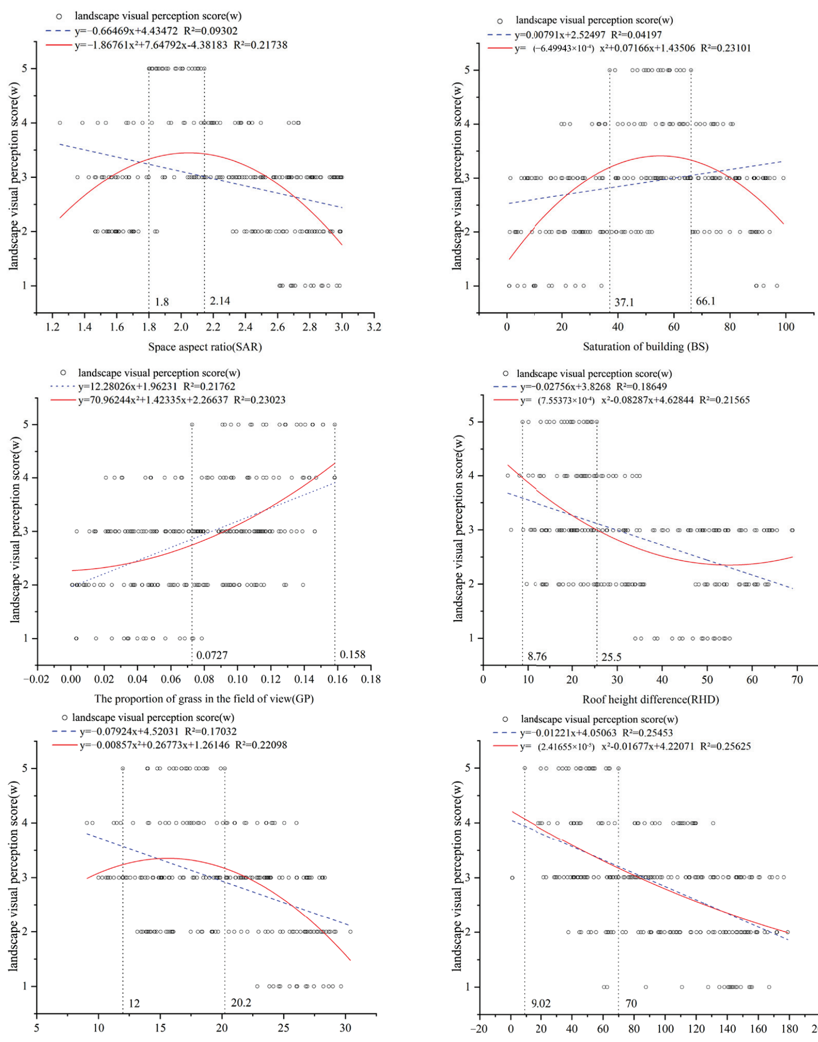


Figure 14. Fitting effects of non-snow season influencing factors and landscape visual perception scores.

As shown in Figure 14, the R-square of the quadratic fitting function between the SAR and W (R^2 = 0.22) is higher than that of the linear fitting function (R^2 = 0.093). In the fitting relationship between the SAR and W, W first increases and then decreases with an increase in the SAR. The maximum value of W appears in the middle of the SAR, and when W is the maximum value (W = 5), the SAR ranges from 1.8 to 2.14.

As for the BS and W, the quadratic fitting function of the BS and W has a higher R-squared (R^2 = 0.23) than the linear fitting function (R^2 = 0.04). There is a positive correlation between the BS and W, with W showing a trend of first increasing and then decreasing with increasing BS. The maximum value of W appears in the middle of the BS range. When W reaches the maximum value (W = 5), the BS ranges from 37.1 to 66.1.

For the GP and W, the quadratic fit function for the GP and W (R^2 = 0.23) has a higher R-square than the linear fit function (R^2 = 0.22). In the fitting relationship between the BS and W, W is positively correlated with the GP, and W increases as the GP increases. The maximum value of W appears at the back of the range of GP values, and when W is the maximum value (W = 5), the range of GP values is 7.27–15.8%.

For the RHD and W, the quadratic fitting function for the RHD and W (R^2 = 0.22) exhibits a higher R-square than the linear fitting function (R^2 = 0.19). In the fitting relationship between the RHD and W, W is negatively correlated with the RHD, and W decreases with increasing RHD. The maximum value of W appears in front of the value range of the RHD. When W is at the maximum value (W = 5), the value range of the RHD is between 8.76 and 25.5 m.

In addition, the quadratic fitting function between the TTH and W (R^2 = 0.22) has a higher R-square than the linear fitting function (R^2 = 0.17). In the fitting relationship between the TTH and W, W first increases and then decreases with increasing TTH. The maximum value of W appears in the middle and front parts of the TTH range. When W is the maximum value (W = 5), the TTH value range is 12–20.2 m.

In addition, the quadratic fitting function between the HC and W (R^2 = 0.26) has a higher R-square than the linear fitting function (R^2 = 0.25). In the fitting relationship between the TTH and W, W is negatively correlated with the HC and shows a decreasing trend with increasing HC. The maximum value of W appears at the front of the range of HC values, and for the maximum value of W (W = 5), the range of HC values is between 9.02 and 70.

3.2.2. Influence Mechanism of Environmental Factors in Snow Season

As shown in Figure 15, the landscape visual perception score (W) correlated with the SAR, BS, and GP, according to the correlation analysis in the snow season environment. The range when W is at its maximum value is shown between the vertical dotted lines.

For the SAR and W, the R-squared of the quadratic fitting function for the SAR (R^2 = 0.20) is higher than that of the linear fitting function (R^2 = 0.14). In the fitting relationship between the SAR and W, W and the SAR first show a positive correlation and then a negative correlation, and W first increases and then decreases with an increase in the SAR. At the maximum value of W (W = 5), the SAR ranges from 2.01 to 2.61.

For the BS and W, the R-square of the quadratic fitting function (R^2 = 0.23) is higher than that of the linear fitting function (R^2 = 0.21). There is a positive correlation between W and BS, and with the increase in BS, the W value shows a trend of first increasing and then decreasing. The maximum value of W occurs when the BS ranges from 67.1 to 88.5. In addition, when fitting the GP and W, the quadratic fitting function (R^2 = 0.25) has a higher R-square than the linear fitting function (R^2 = 0.23). W is positively correlated with GP and shows an increasing trend with increasing GP. The maximum value of W is concentrated in the posterior part of the GP range, and the BS ranges from 8.44% to 14.3% when W reaches a maximum value of 5.

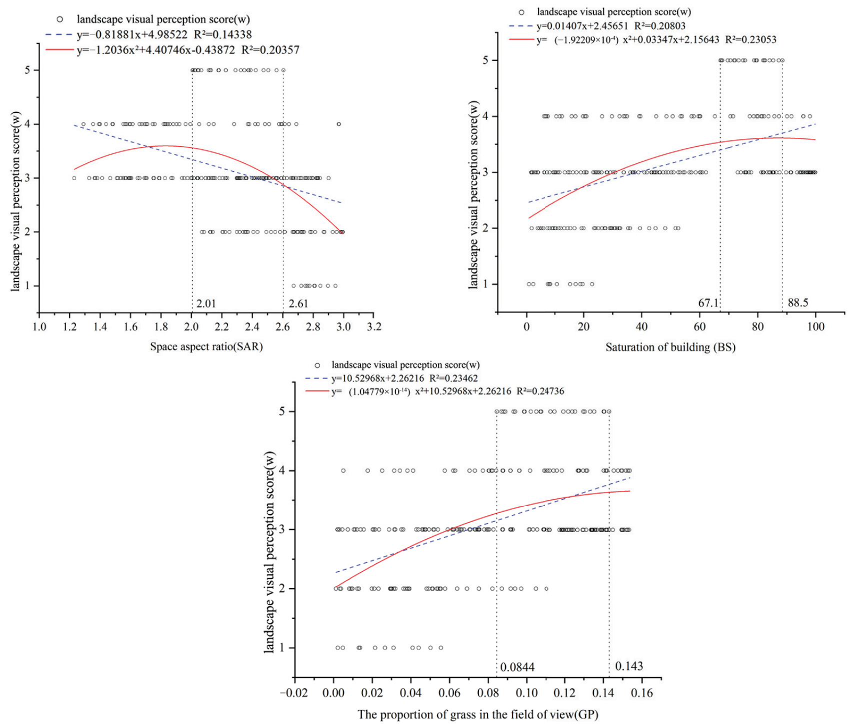


Figure 15. Fitting effects of snow season influencing factors and landscape visual perception scores.

3.3. Threshold Optimization

3.3.1. Machine Learning

This section describes the training and validation processes for machine learning. The prediction effects of the four classification algorithms were compared, and the model structure was adjusted according to the fitting effect. The dataset was derived from the orthogonal experiments in Section 2.4.2. The input dataset consisted of 1685 sets of visual perception variables of leisure landscape environments in the non-snow season and 1697 sets in the snow season, and the output data were the leisure landscape visual perception scores.

Four algorithms (decision tree, SVM, KNN, and ANN) were selected to train the prediction model in the MATLAB-Classification learner toolbox [49–54]; the accuracy could be derived directly after the training was completed, and the greater the accuracy, the more suitable the model proved to be. Figure 16 shows the accuracy confusion matrix of the four algorithm scores in machine learning for the two environmental factors, from which the average prediction accuracy of the four algorithms was calculated.

In the prediction of the landscape visual perception score in the non-snow season environment, the hyperparameters of KNN were as follows: the number of neighbor points was one, the distance measure cosine was used, the distance weight was the inverse distance square, the standardized data were true, and the accuracy was 88.88%, which was better than other classification methods (decision tree: 58.14%, SVM: 71.52%, and ANN: 86.92%). In the prediction of the landscape visual perception score in the snow season environment, the hyperparameters of the KNN were as follows: the number of neighbors was 4, the Mahalanobis distance metric was used, the distance weight was inverse distance, the standardized data were true, and the accuracy was 86.9%, which was better than other classification methods (decision tree: 66.84%, SVM: 72.61%, and ANN: 78.76%).

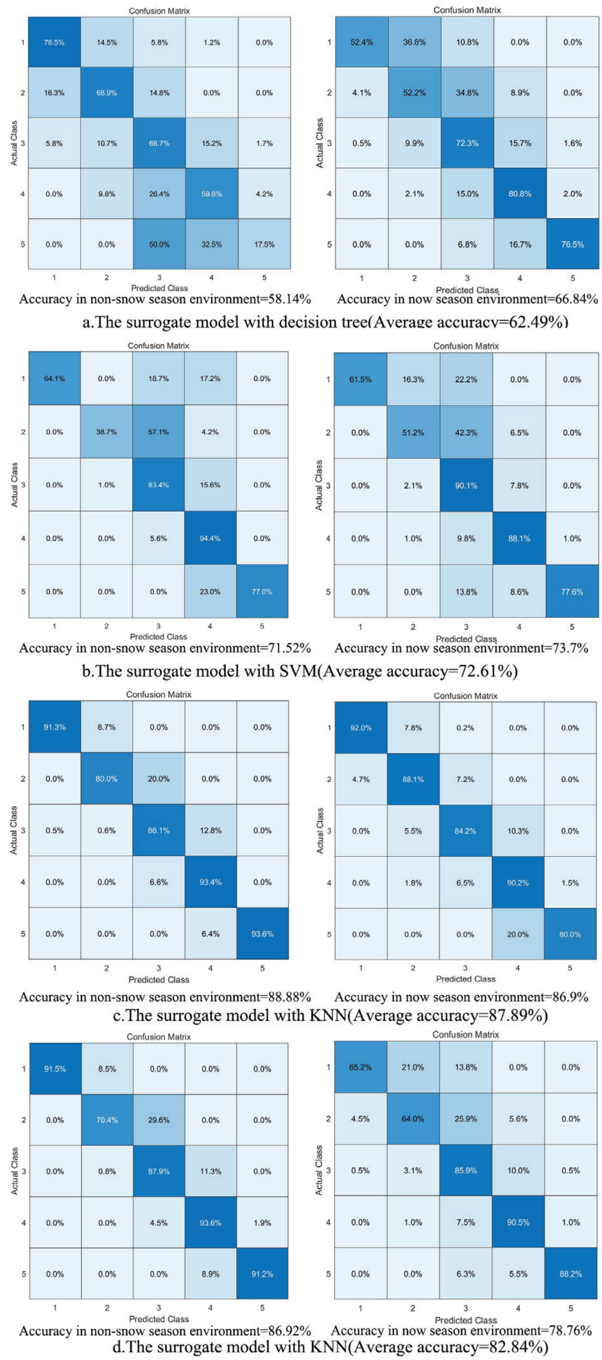


Figure 16. Accuracy confusion matrix for 4 machine learning models (The darker the blue color, the higher the accuracy). (**a**) The surrogate model with decision tree (average accuracy = 62.49%); (**b**) the surrogate model with SVM (average accuracy = 72.61%); (**c**) the surrogate model with KNN (average accuracy = 87.89%); (**d**) the surrogate model with KNN (average accuracy = 82.84%).

In general, as shown in Figure 16, the decision tree (62.49%) and SVM (72.61%) had relatively poor fitting results, and the ANN (82.84%) had a similar but smaller fitting effect than KNN (87.89%).

3.3.2. Optimizing the Threshold

In the genetic algorithm optimization design, the environmental factors in the non-snow and snow seasons were set within a reasonable range for optimization, as shown in Figure 17. For the sake of clarity and aesthetics, the two graphs have different scales for the X and Y axes; the environmental factor variable value at the maximum perception score was obtained from the optimization convergence results. The extreme values of the environmental factors obtained after the iterations were integrated, as shown in Table 5. According to the results of the GA, in the optimization design of a non-snow season environment, this research suggests the SAR should be set to between 1.82 and 2.15, RHD between 10.81 m and 20.09 m, BS between 48.53 and 61.01, TTH between 14.18 m and 18.29 m, GP between 0.12 and 0.15, and HC between 18.64 and 26.83. In the snow season, the extreme values of the environmental factors obtained after the iterations were integrated, as shown in Table 6. According to the results of the GA, in the optimization design of a snow season environment, this study suggests setting the SAR to between 2.22 and 2.54, BS between 68.53 and 82.34, and GP between 0.1 and 0.14.

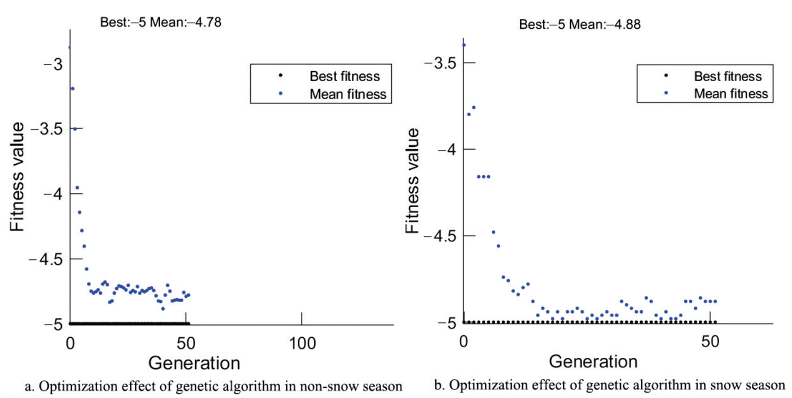


Figure 17. Optimization effect of genetic algorithm. (**a**) Optimization effect of genetic algorithm in non-snow season; (**b**) optimization effect of genetic algorithm in snow season.

Table 5. Optimized thresholds of non-snow environmental factors by GA.

	Solution Set 1	Solution Set 2	Solution Set 3	Solution Set 4	...	Solution Set 30	Range
SAR	1.8795	1.9057	1.821	1.9776	...	2.1485	1.82–2.15
RHD (m)	15.094	10.8099	15.9183	18.1143	...	20.093	10.81–20.09
BS	58.2669	60.2785	48.5304	52.8396	...	61.0109	48.53–61.01
TTH (m)	17.5717	16.7644	14.3164	17.3361	...	18.2912	14.18–18.29
GP (%)	0.125	0.1369	0.1185	0.146	...	0.154	0.12–0.15
HC	19.9477	18.6411	20.6017	25.8764	...	26.8322	18.64–26.83
W (Predict)	5 (4.90)	5 (4.70)	5 (4.85)	5 (4.96)	...	5 (4.84)	5 (4.70–5.0)

Table 6. Optimized thresholds of snow environmental factors by GA.

	Solution Set 1	Solution Set 2	Solution Set 3	Solution Set 4	...	Solution Set 30	Range
SAR	2.2234	2.4057	2.5211	2.3716	...	2.5425	2.22–2.54
BS	68.5324	70.8215	78.5304	72.8396	...	82.3412	68.53–82.34
GP (%)	0.104	0.139	0.115	0.136	...	0.144	0.1–0.14
W (Predict)	5 (4.76)	5 (4.80)	5 (4.90)	5 (4.67)	...	5 (4.84)	5 (4.67–4.90)

4. Discussion

This study attempted to address the research gap of visual perception in outdoor landscape environments in cold regions and obtained the entity elements affecting visual perception in outdoor leisure landscape environments in the non-snow season and the snow season, as well as the appropriate threshold range. In particular, this study is worth discussing in terms of the following aspects.

4.1. Walking with a VR Headset Is More Accurate Than Using a Joystick Remote Control to Obtain Visual Focus

In the validation of VR through the eye tracker and SD questionnaire, although the VR scene perception was slightly different from the real scene, in terms of users' gaze characteristics, the research results in Sections 3.1.2 and 3.1.3 showed that the gaze characteristics of leisure walking between houses in the non-snow season and snow season in the VR scene were relatively close to the actual scene. From the data in Section 3.1.3, walking with a head-mounted VR device in real environments is more realistic and closer to real-world gaze characteristics than using a joystick remote control. Many people prefer web-based research methods, which are good for saving time and money and are easy to access, but these methods lack realism and differ greatly from the actual landscape identification process. Jaewon Han and Sugie Lee's study showed that the results of streetscape evaluation based on VR images differed significantly from the results of streetscape images based on web-based images, and that the VR streetscape evaluation method has better interpretation ability [60]. This study was followed up with a methodological comparative study in which the visual focus of the subjects was obtained in the form of viewing photographs of leisure landscapes, which were compared with the data obtained based on VR images. Similar landscape visual perception scores were obtained by comparing the field scenario questionnaire with the orthogonal experimental questionnaire. In general, considering the similarities and differences in leisure landscape perception between the VR and actual scenes in the snow and non-snow seasons, it is feasible to apply VR technology to visual research on outdoor landscape environments.

4.2. Machine Learning Model Comparison

In Section 3.3.1, the landscape visual perception score prediction effects of the decision tree, SVM, KNN, and ANN were compared. The classification prediction accuracy of the KNN (87.89%) was higher than that of the decision tree (62.49%), SVM (72.61%), and ANN (82.84%). This means that the KNN classification algorithm was the best at predicting the perceived score of landscape spaces in cold regions. Qi et al. used spatial images of landscapes around Mochou Lake in Nanjing, China, with recorded scores to train a convolutional neural network (CNN) to obtain a visual characterization of the vibrancy of urban streets [61]. Differences in accuracy may be due to differences in experimental samples and experimental scenarios. This study can be used in the future to conduct a more comprehensive comparative study of prediction results using ANN, CNN, and other methods.

4.3. Limitation of Subject Group Selection and Leisure Type

Although this study conducted an element screening experiment for residential users and selected as many age groups as possible to participate, the age, physical condition, motion state, and visual focus of the subjects for element screening may be different. These results are valid for the study of leisure walking behavior, but the validity of this method for other common leisure behaviors has not been demonstrated. Other common visual environment studies of in-house leisure activities, such as sitting still [29] and jogging [62], should be conducted and tested in the future. Physiological indicator devices can be introduced in future studies to compensate for existing limitations [63,64].

4.4. Limitations of Screening Leisure Visual Landscape Environmental Factors

A study by Chinazzo, G. et al. confirmed the cross-modal effects of indoor temperature and horizontal illuminance on visual perception [65]. In this study, after actual interviews with the subjects, it was learned that in the snow season environment, the low temperatures in the cold regions would largely affect people's walking thoughts, walking speeds, and modes of travel, which would affect the comprehensiveness of the experiment to a certain extent. Although this study explored the influence mechanism of visual perception in snow and non-snow seasons, the experiment did not consider the influence of physical factors such as the temperature [66], humidity [67], and light environment [68]. In future studies, VR experiments will be conducted in combination with a virtual environment warehouse [69,70], the aim will be to restore the same environmental conditions as the actual scenario and to dress the subjects with physiological indicator equipment, using physiological indicators as supplementary indicators for subjective evaluation, which will help to enhance the accuracy of the experiment. Future research should explore the influence of multiple physical and landscape environmental factors on the visual perception of leisure landscapes to compensate for the limitations of this study.

4.5. Limitations of Research Application and Evaluation Monitoring

Although this study applied machine learning and a genetic algorithm to calculate the parameter design range in the snow and non-snow seasons, the range was not applied in the actual design, nor was it evaluated or monitored. In future studies, the method can be used to extract and test controversial landscape spatial elements in real projects, and it is expected to enable assessing the visual perception of different types of spaces, such as commercial spaces and transportation spaces [16]. Machine learning and genetic algorithms will be used to optimize the light environment [71], establish a parametric VR model, and apply it to an updated design of an actual leisure scene.

5. Conclusions

5.1. Landscape Environment Factors

In the validation of VR through the eye tracker and SD questionnaire, according to the results in Section 3.1.1, in the non-snow season, the attributes of entity elements screened by the SD questionnaire were the SAR, RHD, GP, TTH, BS, and HC. During the snow season, the attributes of the entity elements screened by the SD questionnaire were the SAR, GP, and BS. In Section 3.1.2, the eye tracker data showed that during the leisure process, users paid the most attention to the ground, buildings, tall trees, and lawns in both the non-snow and snow seasons. In addition, through the Pearson correlation analysis in Sections 3.2.1 and 3.2.2, it was concluded that the environmental factors affecting the visual perception of the landscape environment in the non-snow season were the SAR, RHD, BS, TTH, GP, and HC. The environmental factors affecting the visual perception of the landscape environment during the snow season were the SAR, BS, and GP.

5.2. Environmental Factors and Landscape Visual Perception Scores

The influence of factors on landscape visual perception scores in the non-snow season was assessed via the data regression analysis in Section 3.2.1. In the non-snow season environment, the BS and GP were positively correlated with the landscape visual perception score, whereas the SAR, RHD, TTH, and HC were negatively correlated with the landscape visual perception score. With an increase in the BS, the SAR, TTH, and landscape visual perception score (W) showed a trend of first increasing and then decreasing. With the increase in the RHD, the landscape visual perception score showed a trend of first decreasing and then increasing. When the GP increased, landscape visual perception scores increased. When HC in the visual field increased, the landscape visual perception score decreased.

The influence of factors on landscape visual perception scores in the snow season was illustrated by the data regression analysis in Section 3.2.2. It can be seen that in the snow season, the BS and GP were positively correlated with the landscape visual perception score, and the SAR was negatively correlated with the landscape visual perception score. The BS, SAR, and landscape visual perception scores showed a trend of first increasing and then decreasing. When the GP increased, the landscape visual perception scores increased.

5.3. Optimized Variable Ranges

The environmental variable threshold optimization in the non-snow season was calculated in Section 3.3.2. The threshold range of visual environmental factors for leisure landscape perception in a non-snow season environment was obtained. In the environmental design of landscape spaces between houses in cold regions in non-snow seasons, it was suggested that the SAR be set to between 1.82 and 2.15, the range of RHD be set to between 10.81 m and 20.09 m, the range of BS be set to between 48.53 and 61.01, the range of TTH be set to between 14.18 m and 18.29 m, the GP be set to between 0.12 and 0.15, and the HC be set to between 18.64 and 26.83.

The environmental variable threshold optimization in the snow season was obtained in Section 3.3.2. The threshold range of the visual environmental factors for leisure landscape perception in a snow season environment was obtained. In the environmental design of landscape spaces between houses in cold regions in snow season, it was recommended that the SAR range be set to between 2.22 and 2.54, the BS range be set to between 68.47 and 82.34, and the GP range be set to between 0.1 and 0.14.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land13030367/s1, Questionnaire on SD for Visual Perception of landscape leisure spaces between Houses.

Author Contributions: Conceptualization, X.L. and R.Z.; methodology, X.L.; software, K.H.; validation, X.L., K.H. and R.Z.; formal analysis, X.L.; investigation, R.Z.; resources, K.H.; data curation, X.L.; writing—original draft preparation, X.L.; writing—review and editing, K.H.; visualization, R.Z.; supervision, Y.C.; project administration, Y.D.; funding acquisition, Y.C. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: The study was approved by the Medical Ethics Committee of the Harbin Institute of Technology (Ethics No. HIT-2024003). The date of approval was 19 January 2024. All investigations were conducted in accordance with the Declaration of Helsinki on Human Biomedical Research.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Appendix A.1 Decision Tree

Decision trees are used for classification and regression problems [72]. They select the best splitting mode by increasing the learning path of each region and reducing the learning uncertainty. In the following formula, $p(i|t)$ is the ratio of i in node t, i represents the proportion of i, and c indicates the category as Equation (A1).

$$E(t) = -\sum_{i-1}^{c} p(i|t)\log_2 p(i|t) \quad \text{(A1)}$$

Appendix A.2 Support Vector Machines (SVMs)

SVMs, which define the classification of data, were first proposed in 1964. They are typically used for classification calculations and have a good fitting effect [73]. Linear SVMs define the distance to the closest observation in each class as w and operate by finding w and b with the largest margin (bias). In Equations (A2) and (A3), w is an $n \times 1$ matrix and w^T is the transposed $1 \times n$.

$$w^T x + b = w_1 x_1 + w_2 x_2 + \cdots + w_n x_n + b \tag{A2}$$

$$\hat{y} = \begin{cases} 0 \; w^T x + b < 0 \\ 1 \; w^T x + b \geq 0 \end{cases} \tag{A3}$$

In the equation, x^+ indicates when the predicted result is greater than 0, x^- indicates when the predicted result is less than 0, d is the margin of separation as Equations (A4)–(A6), the formula for which is as follows:

$$w^T x^+ + b = 1 \tag{A4}$$

$$w^T x^- + b = -1 \tag{A5}$$

$$d = \frac{2}{w} \tag{A6}$$

To prevent margin errors, the following conditions must be met, and the SVM is transformed into an optimization problem that satisfies the following formula conditions:

$$minimize(w, b)\frac{1}{2}w^T.x \tag{A7}$$

$$subject\ to\ y_i\left(w^T.x^{(i)} + b\right) \geq 1, i = 1, 2, 3, N \tag{A8}$$

Appendix A.3 K-Nearest Neighbor (KNN)

KNN, which is a nonparametric method for computational training and testing samples in a dataset, is often used for classification [74]. It classifies the input values in the existing data into the k-nearest samples. The three distances are defined as the Euclidean, Manhattan, and Minkowski distances. Based on the given distance measure, we determine the point closest to x in the training set. The region adjacent to x covering point k is referred to as $N_k(x)$. Class y of x is determined in $N_k(x)$ according to the classification decision rule. In Equations (A9) and (A10), x_i is the eigenvector of the instance, y_i is the class of the instance, $i = 1, 2, \cdots, N$.

$$y = argmax \sum_{x_i \in N_{k(x)}} I(y_i, c_j), \tag{A9}$$

$$i = 1, 2, \cdots, N; j = 1, 2, \cdots, K \tag{A10}$$

where I is the indicator function. That is, I is 1 when $y_i = c_j$; otherwise, I is 0.

Appendix A.4 Artificial Neural Network (ANN)

In previous studies, artificial neural networks have been used to predict pedestrian evaluations of the environment [50,75]. The structure of an ANN model comprises hidden layers and neurons [76]. The MLP network of input $u(k)$ and target $h(k)$ in hidden layer 1 is as follows in Equations (A11) and (A12):

$$h(k) = \int_2 (w_2 \cdot x(k) + b_2) \tag{A11}$$

$$x(k) = \int_{1} (w_1 \cdot u(k) + b_1) \tag{A12}$$

where $x(k)$ is the output vector of the hidden layer, w_1 is the connection weight matrix from the input layer to the hidden layer, w_2 is the connection weight matrix from the hidden layer to the output layer, and b_1 and b_2 are the number of deviations in the hidden and output layers [77]. The transfer algorithm used between the hidden and output layers is as follows in Equations (A13) and (A14):

$$\int (P) = \frac{1 - e^{-2P}}{1 + e^{-2P}} \tag{A13}$$

$$P = \int (\sum w_i x_i.) \tag{A14}$$

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Article

The Effect of Perceived Real-Scene Environment of a River in a High-Density Urban Area on Emotions

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Abstract: Public sub-health has emerged as a pressing concern in densely populated urban areas. The urban environment, with its innate ability to modulate public emotions, harbors a precious resource in the form of urban rivers, which provide a serene and verdant space. This study focuses on the Liangma River in Chaoyang District, Beijing, selecting two rivers with diverse landscape features as the subjects of research. By employing physiological feedback data in conjunction with a subjective questionnaire, the emotional impact of high-density urban riverside spaces on individuals is quantitatively analyzed. Electrocardiogram (ECG) data, eye movement data, and the positive–negative emotion scale (PANAS) are subjected to data analysis. The study reveals the following key findings: (1) The riverside landscape in high-density urban areas exerts a positive influence on emotional well-being. Individuals in more natural river settings experience greater levels of contentment and relaxation, while those in areas with a higher proportion of artificial elements exhibit increased excitement and happiness. Moreover, scenes characterized by a greater degree of greening have a more pronounced soothing effect on mood. (2) A specific correlation between visual characteristics and emotional fluctuations is observed. The waterfront side of the trail exerts a stronger spatial attraction, and a higher proportion of blue and green spaces significantly contributes to stress relief. (3) The utilization of human-induced engineering technology, which captures emotional changes through physiological feedback, demonstrates a higher level of accuracy and is well-suited for small-scale studies. These findings highlight the potential of arranging diverse types of waterfront footpath landscapes in high-density urban areas and approaching waterfront landscape design and transformation from a novel perspective centered on health intervention. Such efforts hold promise for alleviating the daily pressures faced by the general public and fostering the development of a "healthy city".

Keywords: high-density city; riverside footpath; real-scene environment perception; physiological feedback; landscape preference

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1. Introduction

With the burgeoning population and the influx to metropolitan areas, high density has become an inherent characteristic of numerous expansive cities in China [1]. According to the data disseminated by the Seventh National Population Statistics in 2021, Beijing's population density stood at 1334 people/km^2 [2], epitomizing the attributes of a high-density metropolis. The rapid economic advancement, unwavering efficacy, and multifaceted nature of the city's epicenter have magnetized an influx of inhabitants and resources. Simultaneously, owing to the scarcity of land resources and the preponderance of complex landscape infrastructure, such as towering buildings and thoroughfares, the availability of premium green spaces is severely constrained. In addition, the waterfront areas are adversely affected by the towering structures and the varying characteristics of the high-density space environment, such as the visual intersection in the urban expanse. In light of the increasing population, the issue of public health has emerged as an exigent predicament confronting high-density urban agglomerations [3]. Therefore, the necessity of balancing urban development with the construction of verdant environments has taken center stage, with a focus on offering opportunities for denizens to engage with nature in high-density cities [4], while concurrently mitigating the deleterious repercussions of high-density surroundings on emotional well-being [5,6].

The early studies pertaining to the perception of emotions primarily relied on photographs, cognitive maps, environmental simulations, and other methodologies that employed subjective human descriptions and external behavior [7–9]. However, these approaches suffered from certain inaccuracies and hysteresis [10]. By employing physiological instruments, researchers are able to capture and observe real-time physiological signals, subsequently utilizing computer signal processing and analysis techniques to extract and categorize various emotions. This approach enables the accurate interpretation of neural processes and physiological changes in individuals, facilitating comparative analyses in conjunction with psychological indicators, and has thus emerged as the predominant research methodology [11–13]. Physiological signals such as blood volume pulse (BVP), electromyogram (EMG), electroencephalogram (EEG), electrocardiogram (ECG), electrodermal activity (EDA), salivary cortisol (S.C.), glucose (GLU), electrocardiogram(ECG), and face recognition measurement have been extensively employed in studies examining the natural environment, spatial characteristics of natural environment, urban parks, and the impact of plant landscape composition on human health and well-being [14–19]. Among the various physiological signals, ECG signals possess the advantages of real-time data acquisition, ease of collection, and high accuracy in emotion recognition [20]. In comparison to traditional questionnaire surveys, the utilization of physiological signals for emotion recognition is not susceptible to subjective influences, thereby enabling accurate research results even with a limited number of participants [21,22]. In addition, a significant correlation exists between visual preferences, attention, and emotions [23,24]. Eye tracking technology serves as a common method for measuring individual responses to emotional stimuli. By examining eye tracking focus and attention duration, it is possible to determine the visual preferences of individuals in different settings, as well as the relationship between the public's preferences and landscape [16,24], and landscape complexity [25,26]. The sympathetic response obtained through physiological signals has a higher sensitivity to emotional perception and has been widely applied in existing research on restorative landscapes. However, in existing research, it is often applied to environmental impact studies primarily focused on natural factors. There is relatively little research on high-density urban environments with mixed artificial and natural factors, and there are few studies that combine public eye tracking results in the environment with ECG results to explore the relationship between visual attention and emotion in urban riverside environments.

In densely populated urban areas, rivers meander and converge, representing the most prevalent natural spaces encountered by individuals. The natural environment is more conducive to the recovery of physiological functions than the urban environment [27]. Urban riverside space is the most typical natural space in high-density urban environments and also has a high degree of landscape complexity [28,29]. The urban riverside space, characterized by its complex elements in a high-density urban environment, has emerged as a crucial focal point for addressing a multitude of urban challenges [30]. Therefore, the evaluation and development of riverside landscapes have assumed paramount importance. By examining the impact of different riverside spaces in high-density urban areas through the design and transformation of limited spaces along the riverbanks, the aim is to move necessary activities in high-density cities closer to spontaneous activities and increase the sociality of urban riverside greenways [31], and achieve optimal emotional regulation among individuals, enhance citizen happiness, and thereby become a central focus of research and design pertaining to high-density urban riverside landscapes. It is worth noting that the public's subjective evaluation of complex scenes tends to be less logical and more closely aligned with aesthetic preferences for similar simple types of landscapes [32]. Existing research in the field of neuroscience primarily focuses on the perception of emotions in relation to green landscapes, blue spaces, and complicated urban landscapes [33,34]. The research on river landscapes is also considered as a whole [28,35], and there is little discussion on the differences among different landscape types in the major categories of riverside landscape. In the context of urban renewal, detailed classification of the same type of landscape and targeted improvement of quality have become the future development direction [36]. Studying the existing riverside landscapes for updating and discovering the impact of different types of riverside landscapes on emotions can provide guidance for the future renovation of riverside landscapes.

The measurement of human emotion in real-life settings present a greater challenge [37]. Previous studies have predominantly employed photographs or videos to simulate scenes, resulting in a passive experiential environment that overlooks the study of human perception regarding boundary landscape components [38]. Nowadays, more and more scholars are using VR devices to collect videos of built environments for simulation experiments, though this method is improved compared to the original method of using photos for experiments [39,40]. However, there is a significant difference in emotional perception between subjects in outdoor environments and virtual reality environments, and outdoor environments have a stronger effect on improving emotions [41]. In the assessment of realistic environments, subjects can effectively alleviate fatigue, enhance cardiopulmonary function, and reduce blood pressure by engaging with natural sounds and inhaling negative oxygen ions in blue and green spaces [42–44]. This, in turn, contributes to the enhancement of the positive impact of riverside spaces on emotions and the reinforcement of public health promotion through everyday landscapes in densely populated cities. The advent of portable wearable sensors has made it feasible to capture the counter experience of natural environments [45]. It can be seen that by collecting the emotional perceptions of individuals in constructed riverside spaces, a more comprehensive and objective evaluation of environmental influence can be achieved, thereby facilitating a more appropriate assessment of spatial design.

The limitations associated with the acquisition of emotional perception, the challenges in identifying subtle emotional differences, and insufficient research on the emotional impact of urban riverside environments are addressed in this study through the utilization of physiological signals derived from ECG and eye movement in real-world environments. These signals are further supplemented by subjective feedback obtained from questionnaires. This research, which relies on the physiological signals of ECG and eye movement, and which is based on small sample experiments, attempts for the first time to evaluate the differences in the impact of different riverside landscape features on emotions in a real environment, explore the relationship between visual attraction features and emotional conversion, and propose suggestions for improving riverside landscape transformation, ultimately enhancing its positive guidance for health and providing scientific guidance.

2. Materials and Methods

2.1. Research Context and Subjects

This study was conducted in the vicinity of the Liangma River, situated in the bustling Chaoyang District of Beijing, which represents the epitome of urban development with its embassy area, commercial shopping center, and densely populated residential office area. This location serves as a prominent showcase for the capital city's engagement with the global community, exemplifying a high-density urban setting. The research focused on two river segments located on the northern bank of the Liangma River (Figure 1). The first segment, spanning a length of 500 m, is characterized by towering structures on both sides, with an average channel width of 37 m. The presence of barges and trails in close proximity to the natural environment further accentuates the landscape. The riverbank is strengthened by stone vertical revetments and pine vertical revetments, with slender verdant trees lining the road–river interface. Along the river segment, aquatic plants have been thoughtfully cultivated. The second segment, measuring 270 m in length, features an average channel width of 18 m. It is divided into upper and lower layers, with a height difference of approximately 2 m. A platform green space is interposed between the two layers, while the upper trail runs alongside the railing of the platform green space. The lower trail is situated in close proximity to the river.

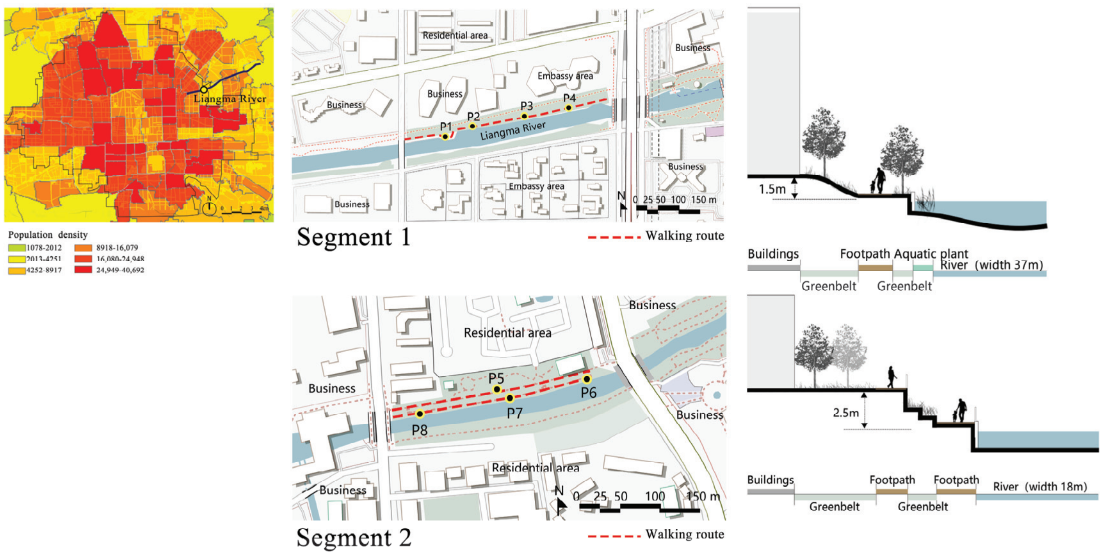


Figure 1. Study site and typical river segments.

Prior to the commencement of the experiment, prospective participants were recruited through an online questionnaire. Only individuals exhibiting emotional stability, physical and mental well-being, non-colored lenses, and access to the designated site were considered eligible for inclusion. The final sample achieved a balanced gender distribution. To ensure the reliability of emotional feedback pertaining to the test, the ECG data collection was conducted in a manner that eliminated the influence of individual momentary fluctuations, thereby bolstering the statistical power of the study despite the relatively small sample size [46,47]. In addition, the dynamic nature of data collection in an outdoor setting posed additional complexities compared to indoor data collection. Therefore, referring to the research of Mohammad et al. [48], a cohort of 13 healthy young adults was selected to participate in the experiment. The data collection took place between 9:00 and 17:00 in November. However, one participant experienced ECG data failure during the data processing stage, leaving a total of 12 individuals with valid data. The male-to-female ratio was 1:1, with an average age of 21 and an average height of 1.69 m.

2.2. Experimental Design

The experimental procedure was conducted in accordance with the following protocol (Figure 2): Firstly, the subjects were directed to the vicinity of the experimental site to receive an introduction to the experimental process and necessary precautions. The subjects' movement trajectory and duration were recorded using the application "two-step path". (1) A portable physiological signal collector (model: Thought Technology-Procomp Infiniti) and portable wearable eye tracker (model: Pupil Labs-pupil invisible) were worn by the subjects. Specifically, three electrodes of the ECG recorder were affixed to the subject's chest at the right margin and intercostal space. Eye movement data was collected as depicted in Figure 3, which showcases photographs of the subjects engaged in the experiment. (2) Physiological data were collected in a high-density urban environment. During a state of calmness, the ECG data were collected for a duration of 2 min prior to entering the segment, serving as the pretest value. (3) Physiological data were collected in an urban riverside environment. Under the guidance of the experimenter, the subjects traversed a distance of 500 m in the riverside environment at an average pace of approximately 1.2 m/s, with channel one representing the upper layer and channel two representing the lower layer. (4) Psychological data were collected. In this study, the PANAS tables developed by Watson were employed to assess mood across 20 items, categorized into two dimensions (Table 1) [49]. Utilizing the Likert 5-point scoring method (1 = not at all, 5 = extremely), dimension scores were assigned, with higher scores indicating a more pronounced emotional state. Following each section of the river course, the experimenter's psychological data were collected through a questionnaire.

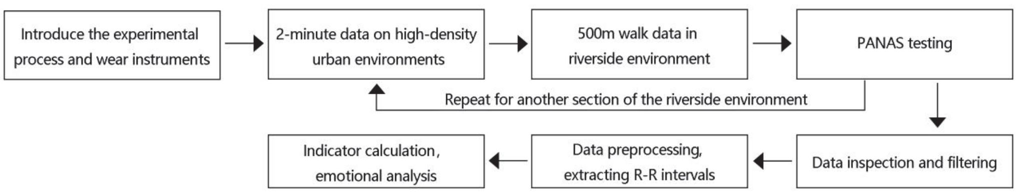


Figure 2. Experimental Procedure.

Figure 3. Experimental process of subjects.

Table 1. PANAS questionnaire content.

Positive Emotions (P.A.)	Negative Emotions (N.A.)
Interested	Afraid
Excited	Jittery
Strong	Nervous
Enthusiastic	Ashamed
Proud	Irritable
Alert	Hostile
Inspired	Scared
Determined	Guilty
Attentive	Upset
Active	Distressed

2.3. Data Processing

The two-dimensional emotion model has been widely employed as a prominent low-dimensional emotion model, renowned for its remarkable recognition capabilities based on physiological factors [50]. This model places significant emphasis on the relationship between valence and arousal dimensions in determining emotions. Valence pertains to individuals' subjective evaluation of their environment, with the two extremes being pleasant and unpleasant. On the other hand, arousal reflects the level of activation of bodily energy associated with the emotional state, with the two extremes being excited and calm. By decomposing different emotions into these two dimensions, they can be effectively mapped onto a coordinate system [51]. In terms of the calculated ECG indices, heart rate (HR) corresponds to potency, while high frequency/low frequency (LF/HF) corresponds to arousal degree. Notably, a positive correlation exists between HR and valence, whereas a negative correlation is observed between LF/HF and arousal. In this study, a biofeedback recorder was employed to measure the ECG signals in a live subject environment, with a sampling frequency of 1000 Hz/s (Figure 4).

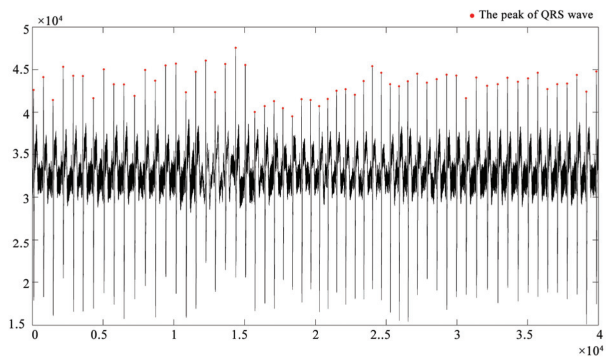


Figure 4. ECG signal extraction R-R interval diagram.

Following denoising, artifact removal, and normalization pretreatment, the collected ECG signals were subjected to analysis. The heart rate variability (HRV) was found to effectively reflect the mood condition based on the ECG signals, as evidenced by the Lorenz scatter plot. Specifically, SDNN (Equation (1)), RMSSD (Equation (2)), HR, and LF/HF were identified as reliable indicators for emotion recognition. Therefore, an optimal feature segment was selected for data testing. In the Lorenz scatter plot, the long axis (representing the length along the 45° straight line) signifies the overall degree of variation in the inner rate of the test time. Conversely, the short axis (representing the width perpendicular to this straight line) represents the difference in adjacent R.R. intervals, thereby expressing the instantaneous heart rate change and reflecting the activity of the vagus nerve [52]. In a normal heart rhythm, the scatter chart should exhibit a concentrated distribution near the 45° angle, displaying a symmetrical comet-like pattern. However, deviations from the 45° angle indicate changes in mood. Notably, lower values of SDNN and RMSSD correspond to a higher positive influence of the environment on human mood. To further study the relationship between visual preference and emotion regulation, four typical scenes were selected in each section. The position and gaze of eye movement, as well as the attention time within a 10 s interval, were extracted to generate an eye movement hotspot map. Through this analysis, human visual preference was assessed, shedding light on the relationship between visual preference and emotion regulation.

$$SDNN = \sqrt{\frac{\sum_{i=1}^{N} (RR_i - \frac{\sum_{i=1}^{N} RR_i}{N})^2}{N}} \quad (1)$$

$$RMSSD = \frac{\sum_{i=1}^{N} \Delta RR_i{}^2}{N} \quad (2)$$

where: RR_i means the number of respiration rate, N means the total number of respiration rate.

3. Results

3.1. Physiological Feedback Results

3.1.1. The Mood Changes of the Riverside Tour

The Lorenz plot in Figure 5 illustrates the significant impact of the riverside environment in high-density cities on the enhancement of residents' mood. The blue data points represent participants residing in a high-density urban environment, while the red data points represent participants in the riverside environment. It is evident that the red data points exhibit a longer spread along the major axis and a wider spread along the minor axis compared to the blue data points. This indicates that in the riverside environment, there is a more pronounced variation in heart rate, a more significant activation of the vagus nerve, and a more intense fluctuation in mood.

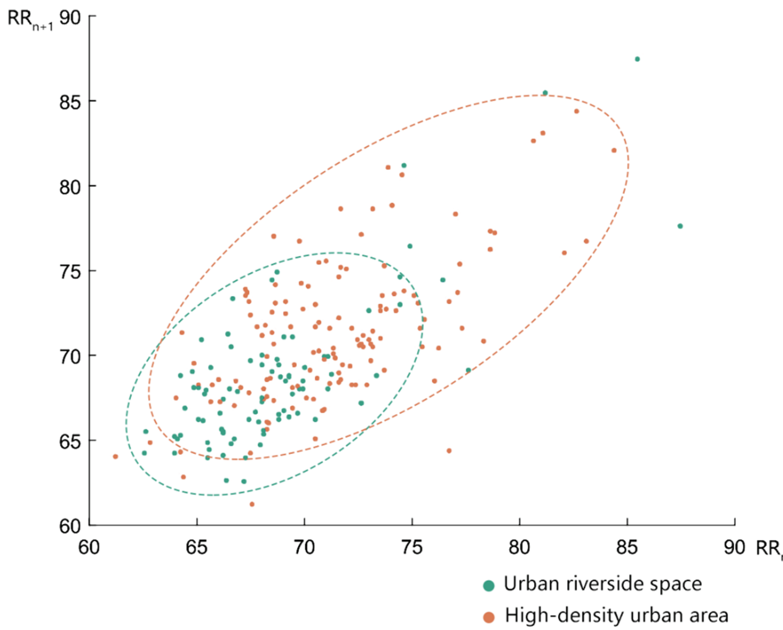


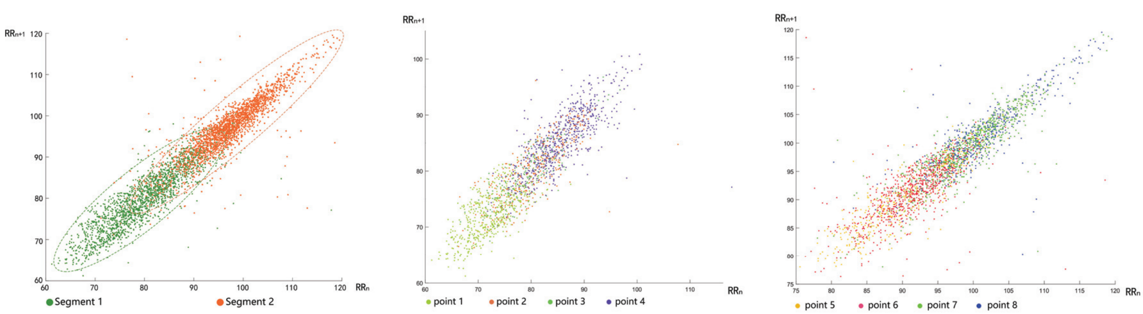
Figure 5. Lorenz plot of high-density urban environment and urban riverside environment.

Through a comparative analysis of the effects of two different segments, namely Segment 1 and Segment 2, it becomes apparent that Segment 1 exerts a more significant positive influence on emotional recovery than Segment 2. The emotional states associated with Segment 1 consist of happiness, satisfaction, and relaxation, whereas Segment 2 elicits excitement and happiness. The ECG data successfully passed independent samples t-tests (Table 2). The SDNN, LF/HF, and HR values of Segment 1 and 2 exhibited significant differences at the 0.01 level, while RMSSD demonstrated significance at the 0.05 level. The data comparisons between the two channel types were statistically significant. The Lorenz plot reveals that the overall heart rate in Segment 1 is lower than that in Segment 2 (Figure 6a). The Lorenz plot in Segment 1 tends to be elliptical, with a longer minor axis, whereas the scatter pattern in Segment 2 tends to be tapered, indicating a greater dispersion along the major axis. These findings suggest that Segment 1 exhibits a more robust positive emotional recovery. Additionally, the experimental results for SDNN and RMSSD in reach 1 were significantly smaller than those in Segment 2. As the pressure is alleviated and emotions develop positively, lower values of SDNN and RMSSD indicate a more pronounced emotional recovery in reach 1 compared to Segment 2. By comparing the data from Segment 1 and 2 (Table 3), it is observed that the average LF/HF index value for Segment 1 is 0.855, which is lower than the corresponding value of 1.246 for Segment 2. This discrepancy can be attributed to the negative correlation between LF/HF and arousal, indicating a lower level of arousal in Segment 2 compared to Segment 1. In addition, the average of HR for Segment 1 is 84.36, which is also lower than the corresponding value of 102.10 for Segment 2. This difference can be attributed to the positive correlation between HR and potency, suggesting a higher level of potency in Segment 2. When projected onto a two-dimensional emotion model (Figure 7), the emotional states associated with Segment 1 tend to be characterized by happiness, satisfaction, and relaxation, whereas Segment 2 elicits excitement and happiness.

Table 2. Independent samples *t*-test.

		Levene's-Test		Mean T-Test						
		F	Sig.	t	df	Sig. (2-Tailed)	Mean Deviation	Standard Error	[95% Conf. Interval]	
SDNN	Equal Variances Assumed	0.221	0.640	−3.103	248	0.003 **	−7.262	2.340	−11.918	−2.606
	Equal Variances Not Assumed			−3.099	241.586	0.003 **	−7.262	2.343	−11.925	−2.599
RMSSD	Equal Variances Assumed	0.185	0.668	−2.448	248	0.017 *	−6.181	2.525	−11.204	−1.157
	Equal Variances Not Assumed			−2.447	243.797	0.017 *	−6.181	2.526	−11.207	−1.154
LF/HF	Equal Variances Assumed	2.488	0.119	−5.568	248	0.000 **	−0.391	0.070	−0.531	−0.251
	Equal Variances Not Assumed			−5.542	214.529	0.000 **	−0.391	0.071	−0.532	−0.250
HR	Equal Variances Assumed	0.067	0.797	−11.375	248	0.000 **	−17.740	1.560	−20.843	−14.637
	Equal Variances Not Assumed			−11.387	241.091	0.000 **	−17.740	1.558	−20.840	−14.640

** At the level of 0.01, the correlation is significant. * At the level of 0.05, the correlation is significant.



(**a**) Comparison of two segments (**b**) Segment 1 (**c**) Segment 2

Figure 6. Comparison of Lorenz plots in two segments and each segment point.

Table 3. Data comparison table of Segment 1 and Segment 2.

Index	Group	N	Mean	Std. Err.	Std. Dev.
SDNN	1	126	32.595	10.146	1.566
	2	124	39.857	11.161	1.743
RMSSD	1	126	26.944	11.234	1.733
	2	124	33.124	11.765	1.837
LF/HF	1	126	0.855	0.253	0.039
	2	124	1.246	0.376	0.059
HR	1	126	84.36	7.397	1.141
	2	124	102.10	6.789	1.060

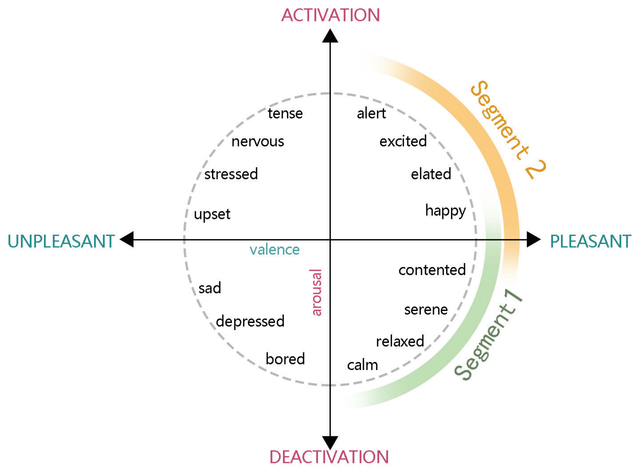


Figure 7. Emotion corresponding to two segments of river in two-dimensional emotion model.

The Lorenz plot in each point of Segment 1 is nearly elliptical (Figure 6b), and the degree of dispersion on the long axis direction is relatively low. The emotional changes are relatively stable, and the heart rate gradually increases over time, with the overall emotional trend leaning towards a positive direction. There are more differences in the Lorenz plot in Segment 2 (Figure 6c). The Lorenz plot in point 5 and 6 of Segment 2 are nearly elliptical, with a longer short axis. The dispersion degree of the long axis is relatively low, and emotions tend to be positive. The Lorenz plot in point 7 and 8 are conical, with a higher dispersion degree of the long axis and a greater range of emotional changes. The positive influence of emotions is weakened, with point 8 being the most nervous.

3.1.2. Visual Attraction of the Riverside Scene

The analysis of the eight river scenes reveals several observations: (1) The populace exhibits a lower focus on complicated urban elements such as buildings and retaining walls, instead directing their attention towards the natural surroundings including plants and water bodies. (2) In scenes characterized by extensive riverside greening in densely populated cities (points 1, 3, 4, 5, and 7), the visual emphasis tends to gravitate towards the waterfront side. Specifically, the line of sight predominantly fixates on aquatic plants, while the greenery near the city side holds less attraction. (3) In environments featuring a high degree of hardening along the trail (points 7 and 8), green plants exert a greater pull on the line of sight. (4) The dispersion of people's gaze along the riverside footpath is directly proportional to the openness of the surrounding area. This dispersion serves as a reflection of individuals' appreciation and preference for the environment. Notably, pedestrians exhibit a more scattered gaze and greater visual perception in naturalistic scenes (points 3, 4, and 5) and scenes with designated rest spaces (point 8)—though planting trees on the waterfront side can hinder the view of the water surface (point 2)—as opposed to complex scenes where pedestrians primarily focus on the surrounding landscape, points with a high degree of hardening, placing greater emphasis on walking and displaying less appreciation for the surrounding landscape.

3.2. Feedback Results of the Questionnaire

Concerning the PANAS score line graph depicting different subjects (Figure 8), it becomes evident that, considering the limited sample size, subjects harbor diverse psychological sentiments towards various types of river landscapes, lacking any apparent tendency. Upon examining the mean comparison of each assessment item (Figure 9), it is observed that if the value of "interested" and "strong" in channel 1 is less than that in channel 2, and if the value of any other term in channel 1 is significantly greater than that in channel 2, four items (“excited”, “inspired”, “determined”, and “active”) exhibit relatively significant changes. Conversely, in terms of negative emotions, no difference is observed between the values of “distressed” and “irritable” in the two channels. However, the value of “afraid” surpasses that of channel 2, while the value of any other term in channel 2 exceeds that of channel 1. Notably, two items (“scared” and “nervous”) demonstrate relatively significant numerical fluctuations.

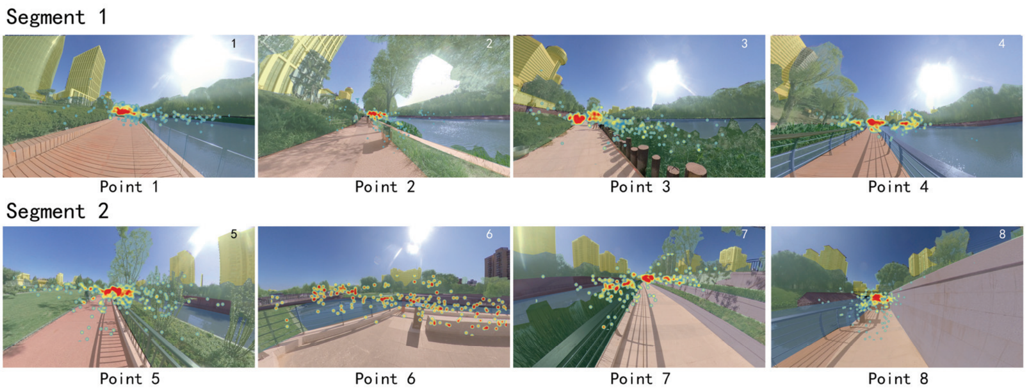


Figure 8. Heat map of eye movement data for each point.

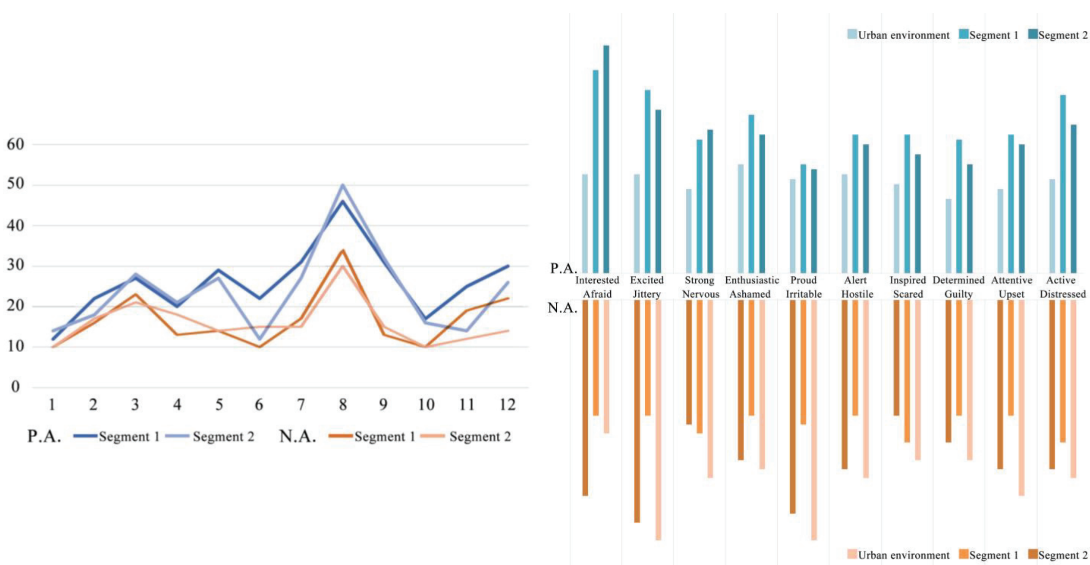


Figure 9. Subjective psychological perception of the subjects.

4. Discussion and Analysis

4.1. The Influence of High-Density Urban Riverside Landscape on Mood

Existing research indicates that urban riverside environments serve as a green haven, offering urban dwellers a space for daily strolls and activities [53], thereby facilitating emotional engagement with the environment and contributing to the overall well-being of the populace. In contrast to the demanding urban setting, the composite landscape comprising the blue and green spaces in the high-density urban river channel exerts a positive influence on emotions [54], with varying effects depending on the composition of the riverside spaces. Here, we show that areas adorned with fewer artificial structures and abundant vegetation, including plants and aquatic flora, exhibit superior stress-relieving properties. Conversely, riverside spaces characterized by extensive hardening tend to disperse the sightlines of pedestrians seeking respite, as they direct their gaze towards the riverside landscape, with a preference for open spaces along the waterfront.

In a more naturalized riverside environment, it has a sustained enhancing effect on positive emotions. In the hardened riverside environment, the positive impact on emotions shows a trend of first increasing and then decreasing.

Building upon the findings, which highlight the pivotal role of plants in capturing visual attention [55], we corroborate the significance of aquatic plants and shrubs in the riverside trail scene. Notably, individuals display greater attentiveness towards aquatic plants, surpassing that directed towards shrubs. Therefore, the intensity of plant presence in the riverside trail environment can be ranked as follows: aquatic plants > shrubs > water. This result highlights the scarcity and value of outdoor water as a precious natural element in the urban environment [56]. By incorporating aquatic plants, the urban river, which is inherently challenging, assumes a more visually natural appearance, enriches the water environment, enhances the overall landscape quality, and significantly alleviates stress.

4.2. Analysis of the Mechanism of Different Types of Riverside Landscapes on Emotions

The emotional impact of urban riverside landscapes, characterized by a high degree of naturalization and a significant proportion of artificial elements, varies significantly. The underlying factors contributing to these differences are as follows:

(1) The visual perception and emotional relief effect of the riverside environment are related to the level of separation between pedestrians and the densely populated urban surroundings. By employing the D/H theory in the analysis of street spaces, the distance (D) between the waterfront environment and the buildings, as well as the height (H) of the buildings, are taken into consideration. In instances where the D/H ratio of the high-density urban waterfront space is <1, a sense of urgency is established, and the complicated landscape adversely affects vision [57]. To mitigate this, the introduction of tall green vegetation between the waterfront city buildings and the waterfront footpath facilitates a green spatial transition, thereby reducing the perceived pressure exerted by the buildings and optimizing the regulatory effect of the waterfront environment on emotions. In addition, the difference in elevation between the riverside space and the high-density urban environment creates a physical barrier, temporarily detaching individuals from the urban setting and providing a respite from the associated pressures and moods [58]. While the level of rigidity in the riverside activity space surpasses that of other trail scenes, varying spatial attributes yield different feedback results. The waterfront activity area offers individuals the opportunity to engage with water and serves as an interactive platform, thereby eliciting a positive emotional impact. Notably, the water surface significantly influences emotional recovery [59]. Due to its high openness and pronounced visual perception, the waterfront activity area exhibits a superior emotional recovery effect.

(2) The difference in the proportion of green space to water bodies in the blue and green space was examined. Existing research indicates that the level of exposure to blue and green space exhibited a strong correlation with individuals' subjective perception of happiness [60]. By incorporating a higher level of greenery and increased water coverage, the secretion of adrenaline and the activation of sympathetic nerves were mitigated to a certain extent, resulting in a more pleasant and relaxed mood [61]. Therefore, this configuration provided the most rejuvenating landscape. In this study, the width of channel 1 was approximately twice that of channel 2, thereby affording a broader and more expansive visual perception of water. Moreover, the elevation difference between the waterfront space and the urban area adjacent to river channel 1 exhibited a gentle slope. The presence of dense vegetation along both sides of the riverside trail contributed

to an exceptional green visual rate and sound attenuation effects. Conversely, the upper space of river channel 2 exerted a specific shading effect, while the lower space featured a complex landscape predominantly characterized by shrubs, a low green visual rate, and heavy artificial traces, thereby easily producing a sense of excitement.

(3) The transition between the riverside space and the urban interface varied in terms of the mode of transition, and the positive emotional promotion effect of visual perception is related to the distance between pedestrians and hard landscapes. Plant communities were found to induce a more calming effect, whereas buildings elicited a more stimulating response [62]. In Segment 1, there is a gentle slope green space separating the waterfront space from the urban interface, which effectively shielded the high-rise structures from view when traversing the riverside trail. Therefore, the visibility of urban development was significantly reduced. In Segment 2, the lower riverside space and the urban interface were separated by a rigid retaining wall, with tall urban buildings situated on the opposite side of the river. As a result, individuals could identify the artificial traces of construction in the riverside space. It is evident that the incorporation of trees, gradual slopes, and vertical greening between waterfront spaces and high-rise buildings can foster a more relaxed and tranquil emotional state.

Under normal walking conditions, people mainly look straight ahead. In Segment 1, there is a height difference between the city and the riverside trail, and plants divide the space between the city and the riverside trail; the impact of architecture on visual perception is relatively small. In Segment 2, the hard retaining wall is tightly attached to the walkway; the artificial landscape with low attention has a stronger impact on pedestrian vision. This situation leads to concentrated vision, low attention to the riverside landscape, and a reduced restorative effect.

(4) Different types of revetments were observed. The difference in height between the riverside trail and the average water level was minimal. A narrow green space flanked the water's edge, featuring stone vertical revetments or pine revetments, with aquatic plants serving as transitional elements. This configuration exhibited a greater tendency towards natural aesthetics, thereby fostering a sense of calm and relaxation. In contrast, river 2 was divided into two tiers of walking systems, with an approximate height difference of 2 m. The lower trail featured vertical revetments and railings, thereby accentuating the artificial nature of the surroundings. Therefore, emotional arousal was higher, resulting in a greater propensity for excitement.

4.3. Determination of Real-Scene Emotion Perception under the New Technology

This study drew on the research methodology of quantifying physiological perception in the field of human engineering technology. It integrated this approach with a psychological questionnaire to address the limitations of conventional subjective questionnaire evaluations. The adaptation of emotions to the environment in most scenarios is subjective to an individual's perspective [63]. When data collection is not convenient in real-world environments, the stability of small sample psychological subjective perception is weaker compared to physiological feedback. Conversely, the ECG data, obtained from a large sample size, were not influenced by subjective evaluation errors, thereby highlighting the potential of human cause engineering technology in obtaining accurate emotional evaluations even with limited sample sizes.

The ECG results revealed that the riverside environment exerted a positive impact on individuals' emotions, with a greater natural ambiance leading to increased feelings of happiness, satisfaction, and relaxation. Conversely, a more artificial riverside setting evoked greater excitement and happiness. The analysis of physiological perception data and the evaluation results from the psychological questionnaire demonstrated consistency. This study presents a novel avenue for interdisciplinary research in landscape architecture, human cause engineering, and other engineering technology disciplines. It introduces a feedback-based evaluation of the influence of landscapes on individuals in landscape planning and design, fostering enhanced interaction between humans and their surroundings. Moreover, it offers a compelling real-time method for evaluating landscapes in natural environments. For instance, by perceiving the emotional feedback effects and influence mechanisms of individuals in riverside environments, landscape design can guide emotional changes based on the expected emotional values of people. This approach proves instrumental in enhancing the impact of landscape planning and design on public health guidance.

4.4. Riverfront Landscape Planning and Design Recommendations

The positive influence exerted by the urban riverside landscape on emotions presents a remarkable opportunity for enhancing the well-being of residents in densely populated urban areas. The waterfront region in high-density cities represents a highly diverse and complex ecosystem [64], serving as a primary spatial medium for promoting human health. In the context of a densely populated city, the design of riverside sites, aided by human engineering technology, facilitates the regulation of public health by considering the collective mood and site requirements. This involves pre-construction environmental adjustments and post-construction emotional regulation, as well as local modifications and enhancements based on physiological feedback. By bolstering the waterfront environment, public health gains can be achieved, thereby meeting the residential needs and acting as a catalyst for physical and mental well-being among the surrounding population, thus realizing the objective of establishing a "healthy city".

In planning and design, using environmental psychology, environment, and behavior as theoretical foundations and exploring the activity patterns of people in outdoor landscape environments can help better develop urban spaces [32]. During the planning phase, it is necessary to fully exploit the potential of the riverside space to enhance connectivity and accessibility between the waterfront area and the city, thereby enabling a greater number of residents to benefit from the convenience and health-enhancing attributes of the urban river space [53]. In the design of the riverside landscape, particular emphasis is placed on strengthening the visual perception of the water surface and ensuring the visibility of the riverside periphery (Figure 10a). In addition, the construction of a diverse range of riverside spaces, including natural walking paths and areas for recreational activities, is undertaken in response to the emotional recuperation requirements associated with the riverside landscape.

To strengthen the presence of the water environment and establish a serene riverside landscape, an overhanging horizontal promenade, positioned in close proximity to the water surface, was incorporated to enhance the visual attraction and perception of the aquatic body (Figure 10f). While adhering to the principle of non-intrusion into the river channel's width, a hydrophilic area and an aquatic vegetation planting strip were introduced onto the rigid riverside revetment. This measure aimed to enhance the visibility and verdant panorama of the riverside's azure expanse. In addition, the foliage density on the urban side of the riverside footpath was enriched, employing trees with lofty branching patterns to offer shade for the riverside trails. This arrangement also served to mitigate the visual impact exerted by urban buildings upon the riverside space. Adjacent to the waterfront trail, a verdant space was designated, predominantly characterized by low-lying grass structures or grass structures that do not obstruct the line of sight (Figure 10e). In close proximity to the water's surface on the waterfront side, an appropriate increase of aquatic plantings was implemented to improve the canopy level of vegetation and enhance the verdant panorama of the canopy. This approach aimed to fully exploit the innate beauty of plant communities while attenuating the presence of urban artificiality (Figure 10d). The implementation of a gentle slope revetment, composed of wooden piers and stones, was explored as a potential substitute for the riverside fence. This alternative was pursued to ensure the safety of riverside recreational activities while mitigating the perception of artificiality. In conjunction with the riverside trail's robust continuity and profound vistas, the introduction of an open canopy facilitated an enhanced perception of the natural horizon and improved the dynamism of the vista (Figure 10b).

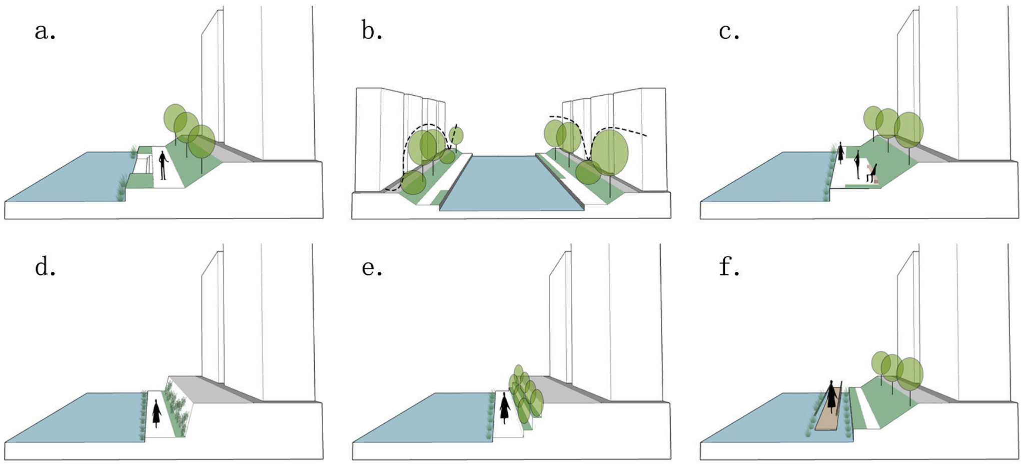


Figure 10. Suggestions for improvement of riverside landscape renovation. (**a**) Planting trees on the city side reduces the visual impact of urban architecture; (**b**) planting trees and shrubs, constructing undulating canopy lines and skylines (the dotted line represents the canopy line); (**c**) constructing waterfront spaces for activities and rest; (**d**) vertical greening with height difference weakens the artificial hard landscape; (**e**) treatment of elevation difference as terrace landscape; (**f**) design water trails to enhance interaction with water.

To create enthusiastic and exciting riverside landscapes in planning and design, low-growing herbs were strategically planted along the waterfront, while a grass structure was established on the urban side. To alleviate plant density, trees were positioned away from the trail. Additionally, the integration of revetment design facilitated controlled flooding of the site. Artificial structures, such as seating areas and sports facilities, were thoughtfully arranged to maximize the social potential of the site and foster social interaction among residents (Figure 10c).

5. Conclusions

Drawing upon small sample empirical research conducted in the field, this paper delves into the utilization of ECG feedback and questionnaire feedback as a means to measure the impact of high-density heterogeneous urban river real-scene environments on individuals' mood and health. By conducting both physiological and psychological assessments, we preliminarily substantiated the following three aspects: (1) urban river landscapes have a positive influence on people's mood and health. In addition, we have discovered that different riverside landscapes possess varying emotional guidance effects, with emotional changes being closely linked to the components of the riverside landscape. People tend to be happy and relaxed in riverside environments with a high proportion of natural elements, while those in areas with a high degree of artificial riverside environments tend to be excited and happy. A more naturalized riverside trail environment has a stronger sustained positive effect on emotions. (2) When traveling along the riverside trail, people tend to prefer scenes with open and high spaces, meanwhile paying the highest attention to aquatic plants. (3) In real-life environments where large-scale experiments are not convenient, the results of small sample experiments obtained through physiological feedback are more convincing than survey questionnaires. However, due to the limited sample size, further development is needed in this research. Based on the current research, designers can design the elements of the site to enhance the experiential environment and amplify the specific emotional guidance effect of the environment, thereby enhancing the health promotion effect of the landscape.

However, this study exhibits several limitations that warrant further study. The absence of a separate quantitative analysis of the river landscape components introduces uncertainty regarding the degree of influence exerted by each component. In addition, there remains a lack of quantitative analysis pertaining to the emotional improvement benefits of the riverside environment subsequent to its transformation and enhancement. In future studies, control variables can be further explored by means of scenario simulation, allowing for a comparative analysis of emotional improvement effects before and after modification. This will enable a more comprehensive understanding of the significance of each element in the riverside scene in relation to emotional improvement.

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Article

Eye-Tracking and Visual Preference: Maybe Beauty Is in the Eye of the Beholder?

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Abstract: The "Content-Identifying Methodology", or CIM, is an approach developed by environmental psychologists Rachel and Stephen Kaplan to understand the landscape characteristics that people find visually attractive. The Kaplans did this by surveying people's landscape preferences and then analyzing the preferences to develop sets of landscape scenes to which people reacted in a similar pattern. The underlying assumption is that a common stimulus or content exists in the photographs of a set responsible for the preference. However, identifying the common stimulus or content in each set or grouping of scenes and how it affects preference can still be challenging. Eye-tracking is a tool that can identify what the survey participants were looking at when indicating their preference for a landscape. This paper demonstrates how eye-tracking was used in two different landscape preference studies to identify the content important to people's preferences and provide insights into how the content affected preference. Eye-tracking can help identify a common stimulus, help determine if the stimulus is a physical or spatial characteristic of the landscape, and show how the stimulus varies in different landscape contexts.

Keywords: eye-tracking; preference; visual; landscape; streetscape; battlefield

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1. Introduction

Is scenic beauty in the eye of the beholder? Many involved in the visual or scenic assessment of landscapes get irritated whenever we hear that old idiom because it implies no agreement among people about what is scenic or beautiful. But maybe that is because we do not know how to find out what is in the eye of the beholder. The objective of this paper is to demonstrate a tool for carrying out that, "eye-tracking".

In order to answer the question "Is beauty in the eye of the beholder?", we must first review a process developed by Rachel and Stephen Kaplan, environmental psychologists at the University of Michigan. The Kaplans use people's preferences for landscapes to identify the physical features and spatial attributes of the landscape that are important to people's experience of the landscape. This methodology is the Category or Content Identification Methodology [1] or CIM (Stephen Kaplan originally referred to this method as a Category-Identifying Methodology, but many now refer to it as a Content-Identifying Methodology). Next, the research of two graduate students at Virginia Tech who used CIM and eye-tracking will demonstrate how eye-tracking can be a helpful tool when undertaking a CIM analysis. Finally, this paper concludes with a summary of how eye-tracking can enhance the process of identifying physical and spatial characteristics that are important to people's visual experience of the landscape.

2. Literature Review

2.1. The Public Role in Scenic Assessment

In the past, there has been tension between those involved in scenic assessment of public lands, often using some objective rating framework, and those who want scenic assessment to represent the public's reaction to the landscape, most often through some survey. Lothian [2] refers to these two paradigms as the objectivist and subjectivist paradigms.

Lothian advocates for using the subjectivist paradigm, saying, "It is more scientific and statistically rigorous" [2] (p. 93). A subjectivist approach based on people's preferences can be scientific and rigorous. The public does not have the technical expertise to assess the scenic value of the landscape, but they have no difficulty expressing how much they like different landscapes. A survey can collect people's preferences for different landscapes. These surveyed preferences can then be analyzed to identify the landscape's physical and spatial characteristics contributing to the preference for each landscape.

While each individual is unique, there is also tremendous agreement among individuals regarding landscape preferences. One reason for this is evolution [3]. Evolutionary survival requires the ability to read and understand a landscape to determine where food, water, and shelter can be found. Survival depends on it. So, part of the reaction to the landscape is innate. It is instinctively within us.

In addition, humans often share a tremendous amount of learned knowledge about the environment. Human landscape preferences are like many other human attributes, such as appearance. We have little difficulty telling people apart because they are each different. However, if someone walked into a room with three eyes or an ear on their forehead, we would all gasp because they are different. So, people are also the same, but within bounds.

However, knowing how much someone likes a landscape does not tell us why they like it. Landscapes are complex, with many combinations of physical and spatial attributes that can influence people's reactions to them. How can the results of a preference survey be turned into something helpful for managing the physical landscape?

2.2. Content-Identifying Methodology

Rachel and Stephen Kaplan, environmental psychologists at the University of Michigan, developed a method of analysis (CIM) [1] that uses the results of a preference survey to identify categories of landscape content based on the physical and spatial characteristics, to which people are reacting. Thus, people's preferences can provide knowledge on how to manage landscapes consistent with public preferences. This analysis method is well documented in Kaplan's book, *The Experience of Nature* [4].

The CIM procedure categorizes landscapes or groups of landscapes according to a common pattern of preferences across a group of survey respondents. Photographs are used as a surrogate for landscapes in the preference surveys. Survey participants are asked to provide their preference for each scene on a 1 to 5 Likert scale, with 1 being not preferred at all and 5 being preferred very much [5]. The CIM procedure then uses a factor analysis to group or categorize scenes with a similar pattern of preferences. The groupings of scenes are called dimensions.

Note that the scenes are not grouped based on the similarities in the magnitude of the response. Instead, each category or dimension is based on a similar response pattern across the group of survey participants. The underlying assumption is that if people are reacting consistently to a group of scenes, then there must be a common stimulus in each group of scenes.

Each cluster or grouping of scenes must be visually examined to determine the common stimulus. This involves judgment. Often, there are very obvious common physical or spatial elements in each group of scenes. The common stimuli may not be as obvious in other dimensions or groupings of scenes. The purpose of this paper is to demonstrate how eye-tracking can be used to help understand the common physical or spatial content of the scenes in a dimension. Two additional aspects of this procedure worth noting are dimension preferences and how scenes are sampled for use in the survey. An overall dimension average can be determined by averaging the preferences of all survey participants for the scenes in each dimension. This provides a sound overall sense of how the content or spatial organization influences people's preferences. In addition, eye-tracking can help determine why scenes with a common stimulus or content may vary in preference or what other landscape characteristics influence preferences.

Since the procedure involves collecting a sample of landscape scenes for a survey, some assume it should be a random sample. However, this type of sample will not work with a CIM analysis. Different types of landscapes vary in their frequency of occurrence. It is possible that a potentially highly preferred landscape is relatively rare and may not show up in a random sample. The survey sample should be selected to represent the range of different landscape types in the study area, with at least three of each possible type [4]. Determining the landscape types is carried out by systematically photographing the landscape and taking many more photos than are needed for the survey. Copies of the photos are then laid out on a table, and a final sample is selected by eliminating extras and making sure there are at least three of each landscape type.

2.3. Eye-Tracking

The use of eye-tracking in research has grown tremendously over the past 30 years, both in terms of types of applications and in computer technology. There is a plethora of literature on eye-tracking. Horsley's book [6] documents 50 applications of eye-tracking research. The breadth of applications speaks to the perceived power of eye-tracking. It can be used for everything from tracking the movement of the eyes of clinicians viewing electrocardiograms [7] to eye-tracking to provide information for marketing purposes. Most eye-tracking studies have not involved landscapes or scenic assessment. There are a few studies, however, that involve eye-tracking while looking at the landscape. The eye-tracking results from these studies have been engaging in terms of the landscape content people focus on. However, it has been difficult for researchers to determine how the eye-tracking content relates to peoples' preference for different landscapes, which is ultimately a landscape management goal. A study in 2022 examined the potential of eye-tracking software for analyzing landscape preferences [8] and found, "Thus, our findings indicate that the analysis of eye-tracking hotspots can support the identification of important elements and areas of a landscape, but it is limited in explaining preferences across different landscape types. Future research should therefore focus on specific landscape characteristics such as complexity, structure or visual appearance of specific elements to increase the depth of information obtained from eye-tracking simulation software" [8] (p. 4). This is precisely what the author of this paper is carrying out. This study demonstrates how eye-tracking can identify landscape characteristics or content related to the landscape based on a CIM preference-based analysis.

3. Method

3.1. Study Objectives—Eye-Tracking as a Tool

CIM has been around for quite a while, but there are still many people who do not understand CIM. One objective of this paper is to demonstrate what CIM does and how it can be better understood with the use of eye-tracking. Eye-tracking is identifying what a survey participant is looking at when they rate their preference for a scene. This can be recorded as a hot-point on the scene being viewed. Multiple viewpoints from different survey participants can also be recorded, creating a heat map, and can reveal something about the physical content and spatial organization of the scene that is being viewed. Eye-tracking can be used to examine reactions to multiple scenes in a dimension, thus helping to understand the common stimulus of CIM but also how the content can vary within a dimension and how it influences people's landscape preferences.

3.2. Eye-Tracking Examples

Two Virginia Tech graduate students used eye-tracking to assist in interpreting CIM dimensions as part of their research. Both students were strong and thorough researchers, committed to understanding how people react to different environments. One student, Seth Estep, was a master's student (MLA) [9] interested in urban pedestrian environments. The other student, Shamsul Abu Bakar [10], was a Ph.D. student interested in Civil War battlefield sites that were being preserved and interpreted at National Parks and National

Monuments. There is not enough room to present each student's entire project. Instead, each student's use of eye-tracking will be described, and their results will be summarized. Two or three examples from each study will demonstrate how eye-tracking can assist in identifying spatial and physical content and other factors influencing the content of CIM dimensions.

Some readers might ask, what do pedestrian environments and battlefields have to do with visual assessment? It is essentially the same process. Landscape preferences are an easy way for people to express their reactions, drawing on what they know about different types of landscapes. It is very natural. People make many preference decisions every day; examples are what to eat for breakfast, what to watch on television, and what tasks to complete that day, to mention a few. So, the context and mental factors of a preference decision may differ. However, the process of expressing preference is the same, whether it is a preference for a battlefield interpretation or a reaction to a natural environment. The mental process of making these is essentially the same. CMI identifies landscape content underlying the preferences, and eye-tracking assists in understanding the nature of the content and how it affects the experience of a landscape.

4. Results

4.1. Pedestrian Streetscapes

Seth's research project intended to identify the physical and spatial elements of urban streetscapes that make the environment more attractive to pedestrians, thus encouraging them to walk to work. He obtained permission from several offices in the Washington, D.C. area to email their employees, asking if they would volunteer to complete an online preference survey. Seventy-five office employees completed the survey and provided their preferences on a 5-point Likert scale for 38 scenes of urban street landscapes. The mean scene preferences ranged from 1.85 to 4.52. The CMI analysis of these scenes generated five dimensions. Since the survey was online and on different computers, the computer could not be used to track eye movement. Instead, the survey participants were told to use their computer mouse and click anywhere within the image on the element most influential to their preference rating for that scene. These are called hot-points. The responses were combined to create heat maps for each image. If the hot-points on the heat map are close together, the colors on the map are yellow and red, appearing to be hot. The heat maps can assist in interpreting the preference dimensions in three ways:

1. They can help identify the common stimuli of each dimension.
2. They can help determine whether the stimulus is a physical element or a spatial arrangement.
3. Heat maps can help determine factors causing variation in the mean preference of the scenes within a dimension.

All of the scenes in Dimension 1, the dimension with the highest mean rating ($\bar{x}$ = 3.72), depict a content of broad ground planes with vegetation providing a sense of spatial containment. The heat map for Scene A2 in this dimension (Figure 1) has the second highest mean preference ($\bar{x}$ = 4.2), which supports this as the common content for this dimension.

The hot-points are tightly clustered on or under the vegetation that forms a canopy over the broad pedestrian space. Hot-points clustered in this manner suggest a spatial aspect to the content. Note that the bollards in the scene do not have hotspots on them, suggesting that they do not influence visual preference. The role of bollards as an influential content will be important in another image shown later in this paper.

The scenes in the second dimension, Dimension B, have many of the characteristics of the Dimension A. However, the scenes also contain human-made objects that influence visual preference. Scene B7 ($\bar{x}$ = 3.75) (Figure 2) is in this dimension and has hot-points clustered around different small human-made objects. The fact that human-made content detracts from preference is easily confirmed in the heat map. Most of the hot-points are on the bike rack, sign, and small structure, confirming that human-made structures are influencing preference for the scene. By comparing the means for the cluster of points around the bike rack and those around the covered structure, it is also possible to determine if one of these human-made features had more of a negative influence on preference for this scene than the others.

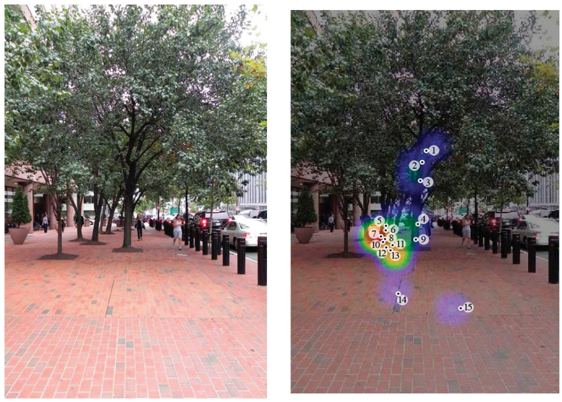


Figure 1. Scene A2 from Dimension A is on the left with a heat map of the scene on the right. Dimension A has the highest mean preference among all the dimensions. Scene A2 is the second most preferred scene in Dimension A. The common content of Dimension A is a wide pedestrian area spatially defined by trees or vegetation. Most of the points on the heat map are located on or under the trees, defining a space. Thus, confirming spatial content is important to people's preference for this dimension.

Figure 2. Scene B7 from Dimension B is on the left and the heat map for this scene is on the right. Dimension B has many characteristics similar to the scenes in Dimension 1, with a wide pedestrian area. However, the scenes in Dimension B also contain human-made content that detracts from the preference. There are hotspots on the bike rack, a small structure, and a sign.

Another scene, B3, is in the same dimension (Figure 3) but has an even lower mean preference ($\bar{x}$ = 2.75). A large cluster of hot-points on the human-made grates and metal covers on the sidewalk indicates a stronger negative influence of this physical content, accounting for the lower mean preference. Eye-tracking helps us see what the content or stimuli of a dimension are and how the similar content can affect preference differently. The human-made content of this scene is visually very evident and has a more substantial negative impact than the human-made content of Scene B7.

Figure 3. Scene B3 from Dimension B is on the left and a heat map of this scene on the right. It is the third most preferred scene in this Dimension B. The common content of is a wide pedestrian area with human-made content that detracts from the preference. The heat map shows that almost all of the hot-points are located on the grates and steel covers on the sidewalk, causing a negative influence to preference.

Eye-tracking can show the complex relationships between elements affecting human preference. Lastly, Scene B5 (Figure 4) is also in the same dimension but with a much lower mean preference ($\overline{x}$ = 2.16). The landscape in the scene is flat and open but lacks vegetation. The critical observation is that many hot-points are clustered on the bollards. As noted previously, there are no hot-points on the bollards in Scene A2 (Figure 1). Scene A2 has much more visual content in the image. This demonstrates the dynamic role that some content can play in people's preferences. When a scene lacks other positive content, like vegetation, attention quickly falls on negative content that is not noticed in a more visually complex landscape. Negative content can have a stronger effect if there is no positive content to distract attention from potentially negative content. Eye-tracking can help to understand how and why a viewer reacts to a scene.

Figure 4. Scene B5 from dimension B is on the left and the heat map for this scene is on the right. It is the least preferred scene in dimension B. The common content of dimension B is a wide pedestrian area with human-made content that detracts from the preference. The effect of the human-made content is confirmed in the heat map.

4.2. Civil War Battlefields

Shamsul's research was on Civil War battlefields, which are an unusual type of landscape for visual assessment. This type of content was very unusual for landscape assessment. It is a completely different context for landscape preference. He was not interested in scenic beauty or visual landscape assessment. He was interested in how a battlefield site could be preserved and interpreted. What do people want to see when they visit a historic battlefield site? Most battlefield sites are green and peaceful today. So, he used photographs of battlefield landscapes taken during and immediately following Civil War battles. Historic photos from many different battlefield sites were used in his study. Shamsul obtained permission from the U.S. Park service to administer an on-site preference survey to visitors at five different American Civil War battlefields:

1. Chickamauga and Chattanooga National Military Park;
2. Shiloh National Military Park;
3. Manassas National Battlefield Park;
4. Antietam National Battlefield;
5. Gettysburg National Military Park.

Participation was voluntary. Shamsul surveyed 242 battlefield visitors. A five-point Likert scale was used to determine visitor preference for thirty-eight battlefield scenes. A CIM analysis produced six dimensions.

- Dimension 1—Civilian ruins/outcomes of war.
- Dimension 2—Large artillery in battle positions.
- Dimension 3—Soldiers in encampments and defensive posts.
- Dimension 4—Civilian structures on battlefields.
- Dimension 5—Battlefield vantage points and viewsheds.
- Dimension 6—Soldiers and civilians in posed positions.

Eye-tracking confirmed the common content of each dimension. For example, the scenes in Dimension 2 (Figure 5) are depicted with their scene number and mean preference. All of the scenes contain large artillery pieces and soldiers. The mean preference for each scene is quite high. This demonstrates that the participants could express their preferences in different contexts. The participants understand that they are providing their preferences for what they want to see in historical exhibits about the Civil War, which would be different than what they would prefer in a scenic landscape assessment. To avoid shocking the survey participants, gruesome pictures of dead and injured soldiers on the battlefield were not included in the survey. However, as part of the survey, the participants were asked if they felt it would be appropriate to include gruesome battlefield images in interpretive exhibits if the viewers were given adequate warning ahead of time. Most people responded to this in the affirmative. Some felt it was important to include such images to understand that war is gruesome.

Computer eye-tracking could not be carried out in the field because of the equipment required. Instead, eye-tracking was carried out with a subset of participants in a laboratory on the Virginia Tech campus. Two connected computer monitors were set up for eye-tracking (Figure 6). One was set up to record the participants' preferences and eye movements (eye-tracking). The second computer monitor was used by the researcher to monitor the survey participants and ensure the eye-tracking software worked correctly. For a more detailed description of the setup, see the paper by Bakar and Miller [11].

Several types of eye-tracking data were collected as the participants' eyes moved over the image, and the participants made sense of the image. The heat maps are created by recording the collective locations on the scene where the participant's eyes finally came to a rest. This produces a heat map similar to those in the first study described above. Figure 7 depicts a heat map for a scene in Dimension 2—large artillery and soldiers in battle position. Dimension 2 has the highest mean preference rating among all the dimensions. Knowing that they would see Civil War battlefield images, the survey participants found these to be interesting and highly preferred.

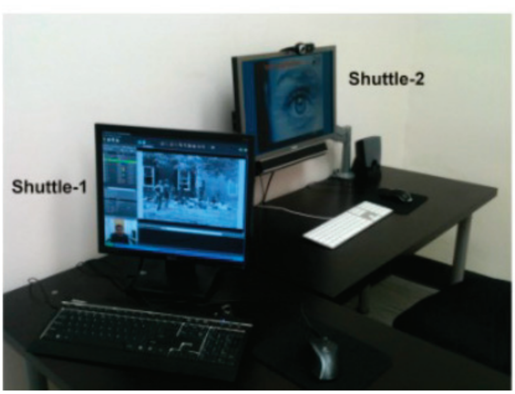
Image 33 ($\bar{x}$ = 4.05)

Image 24 ($\bar{x}$ = 4.04)

Image 28 ($\bar{x}$ = 3.81)

Image 31 ($\bar{x}$ = 4.14)

Figure 5. The factor analysis of the survey preferences revealed the scenes above for Dimension 2. The content in each of the scenes in Dimension 2 ($\bar{x}$ = 4.01) is the presence of large artillery and soldiers in battle positions. Note the relatively high mean preferences. The respondents provided their preference for Civil-War-scene-appropriate interpretive exhibits.



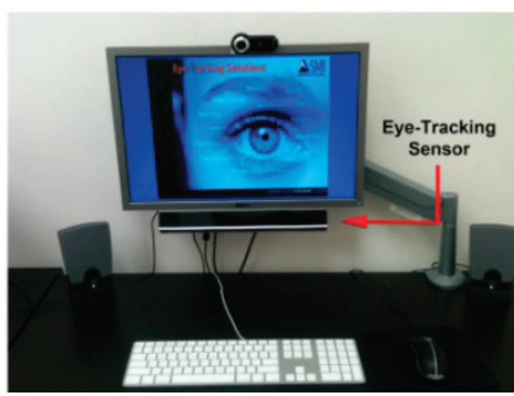


Figure 6. Two shuttles were used for eye-tracking. Shuttle 1 monitors the survey participant as they provide their preferences for each scene. Shuttle 2 has an eye-tracking sensor at the bottom of the screen. The eye-tracking sensor is calibrated for each participant before they begin the survey.

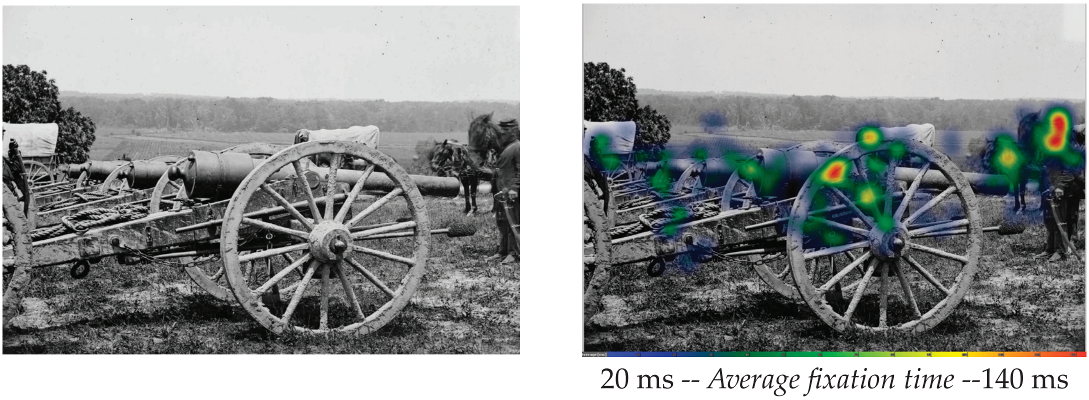


Figure 7. This is an example of a heat map produced by eye-tracking for Scene 28 ($\overline{x}$ = 2.86), including the average fixation time, or the average amount of time in milliseconds it takes the viewer's eyes to become fixed on an object.

Many of the heat maps generated by the eye-tracking software demonstrated an interesting phenomenon. There were people in many of the scenes. The people, and particularly their faces, attracted the attention of the survey participants and were often the location of hotspots, as Figure 8 depicts. Most visual preference studies exclude people from the scenes being rated because the researchers want the participants' reaction to the landscape features, not people.

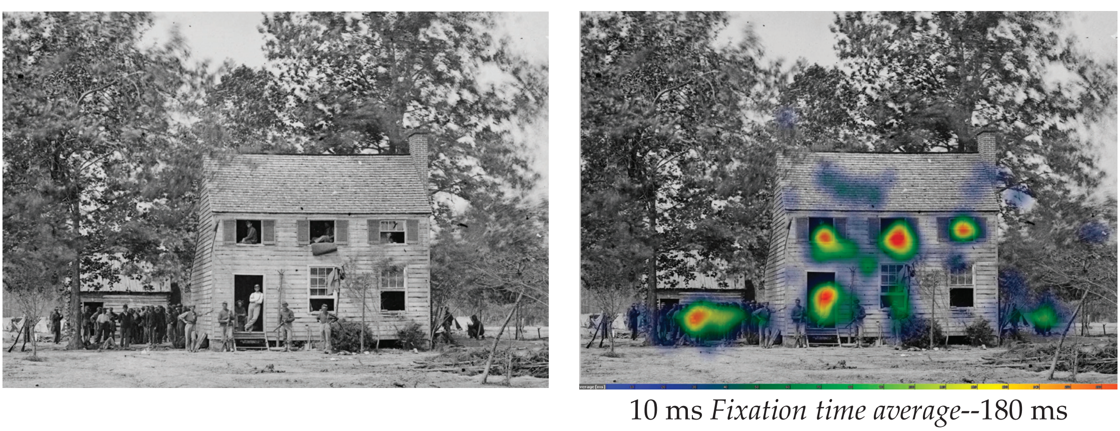


Figure 8. The heat map indicates that the eyes of the survey participants tend to fix on people in Scene 28 ($\overline{x}$ = 2.86).

However, battlefield scenes often include people. In spite of the hotspots on the people, it did not seem to affect their reaction to the dimension content. It seemed that this was almost an innate reaction, that while their eyes fixated on the people, they were still able to react to the other content of the scene.

An excellent example of this is Scene 28 ($\overline{x}$ = 2.86) in Figure 8, in a dimension whose content was "civilian structures in battlefields". While all the images in this dimension contained civilian structures, the hotspots on scenes with people, like Scene 28, were on the doors, windows, or next to buildings where people were located. Perhaps the fact that the people are not close and that survey participants expected to see people allowed other content to still influence their preference.

Two additional data sources from eye-tracking are the fixation time (Figure 9) and scan-path. Fixation time is how long it takes a participant's eye movement to become relatively fixed. The eye scanner records the participant's eye movement as they comprehend a scene. More complex scenes may require more time to comprehend. This can be valuable information for the researcher who is trying to determine relevant scene content and influential factors. Fixation time may help interpret more complex CIM content.

Figure 9. An example of a scan path for Scene 27 ($\bar{x}$ = 2.86) that depicts the path that a survey participant's eyes move across the scene as they make sense of a scene. The line depicts the path the eye followed, and the circles are the places where the eye paused when scanning the scene. The size of the circles depicts the relative amount of time each pause lasted.

The scan-path records a participant's eye movement as they comprehend a scene (Figure 9). The order of the scan or what attracts viewer attention first may help determine what CIM content is more dominant. The circles indicate where the eye pauses and changes direction. The size of the circle indicates the length of time that the eye is focused on a specific location in the scene. While trying to make sense of a scene, the survey participant's scan-path could provide essential insights into understanding the content and its impact on people. It can be helpful to know how long it takes someone to understand what they are looking at and the order of what attracts their attention first.

5. Summary and Conclusions

This paper demonstrates how eye-tracking from two studies of very different landscape types can be used to reveal and interpret CIM content. Heat maps were generated by eye-tracking, and we are able to

- Assist in a CIM analysis in very different contexts.
- Identify physical content that is important to people's preferences.
- Identify spatial content that is important to people's preferences.
- Identify if there were multiple types of content influencing people's preferences, both positively and negatively.
- Identify the path or the order of the elements that were looked at in order to reach a preference decision for a scene.
- Identify the complexity of landscape content and combinations of content by how long it takes people to reach a preference for scenes with different content.

This paper is a very modest examination of how eye-tracking can assist in a CIM analysis. Further studies are needed to demonstrate how understanding CIM content can be turned into knowledge useful for landscape planning and design, thus confirming Lothian's [2] claim that the subjectivist method "is more scientific and statistically rigorous" [2] (p. 93). Eye-tracking is a rapidly progressing area of research. More research is needed not only to identify preferred landscape content but also to understand how patterns and the density of that content influence preference. Computer technology is developing rapidly. We can now use glasses or goggles to track eye movement as people move through the environment. This new technology will enable eye-tracking research on scenic byways and other scenic designated landscapes.

The phrase "beauty is in the eye of the beholder" is an idiom. An idiom is a phrase that contains a figurative meaning that differs from the phrase's literal meaning. In this case, the idiom meaning is that beauty is completely subjective with no agreement among people. This is ironic because the literal meaning may be more accurate. The eye is the way most people take visual information into their brain when determining what they like about the landscape. This paper demonstrates how eye-tracking can assist in identifying common content that influences people's preferences in a landscape. So, maybe beauty is in the eye of the beholder—if you know how to find it.

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Communication

In Pursuit of Eye Tracking for Visual Landscape Assessments

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Abstract: Visual quality and impact assessments have historically relied on experts to formally evaluate the visual properties of a landscape. In contrast, environmental psychologists have studied subjective landscape preferences using ratings and surveys. These two approaches represent, respectively, the "objectivist" and "subjectivist" paradigms within visual landscape research. A gap, however, exists between these approaches: actual observation behaviors. In this paper, we argue for the inclusion of eye-tracking research in visual landscape assessments as a critical bridge between objective landscape qualities and subjective visual experiences. We describe the basics of eye-tracking methods and data types to introduce the role of eye movements in landscape preference formation. Three-dimensional immersive virtual environments are particularly useful for collecting these types of data, as they allow for quantification of the viewed environment's spatial and scene metrics in addition to providing eye-tracking capabilities at sufficient resolutions. These environmental and behavioral data can then be consolidated and analyzed within existing GIS platforms to draw conclusions about environmental influences on observation behaviors. While eye tracking may eventually contribute directly to the practice of visual quality or impact assessments, the near-term benefits of this work will most likely center around contributing to the objectivity and defensibility of assessments through validation and methodological recommendations.

Keywords: eye tracking; viewing behavior; visual resources; landscape assessment; spatial analysis; landscape preference

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1. Introduction

In the last fifty years, methods for documenting baseline and altered visual landscapes have primarily relied on objective measurements of physical landscape characteristics [1]. In that time, researchers have regularly explored opportunities to improve the validity and reliability of these assessments [2–5]. Most of these assessments rely on expert evaluations and, occasionally, include public comments and preference surveys to produce visual impact sensitivity analyses. From a theoretical perspective, expert evaluations and public surveys represent contrasting approaches to the question of landscape quality. On the one hand, professional assessments tend to assign scenic quality as a value inherent in the landscape. On the other hand, sensitivity analyses assume that scenic value is a subjective experience inherent to the viewer. As such, the juxtaposition of expert and public within assessments represents a combination of objective landscape qualities and the more subjective visual perceptions of viewers [6]. These binary approaches, despite being written about extensively, have left significant gaps concerning the holistic integration of methods and data types covering the full spectrum from raw spatial data through perception to preference.

On either side of these gaps, both paradigms have developed numerous methodologies for measuring their respective scenic landscape constructs. Objectivist methods, like the US Forestry Service's former Visual Resource Management (VRM) system, assigned values using formal design elements. The VRM system used scenic quality evaluations, sensitivity analyses, and distance zones to classify landscapes based on factors like landforms and vegetation. The US Army Corps of Engineers introduced another objectivist method, the Visual Resource Assessment Procedure (VRAP), for standardizing esthetic considerations and focusing on expert-defined classifications supported by public input. In contrast, subjectivist paradigms assess cognitive, emotional, and physical experiences. For example, the Scenic Beauty Estimation Method (SBE) rates landscapes based on viewer perceptions and internal judgments [7], and these methods have evolved to incorporate newer surveys and physiological measures [8]. Other studies explored landscape preferences related to natural versus developed landscape scenes. For example, Kaplan's [9] framework links preferences to understanding, exploration, coherence, and complexity, and similar work has contributed to the rise of cognitive [10] and esthetic–spatial approaches [11]. Additionally, Gibson's ecological perception theory emphasized perceived affordances within a landscape, which, in turn, shaped esthetic preferences based on the viewer's needs [12].

The debate between paradigms centers on whether esthetics are inherent qualities or subjective experiences. While objectivist methods dominate current visual impact assessment practices, calls for combining expert and public assessments and exploring experiential changes highlight the need for a balanced approach [6]. Both approaches incorporate aspects of spatial, scene, and preference rating variables, but a crucial link between these factors remains missing: the observers' viewing behaviors.

It should be noted that this paper uses terms such as "landscape assessment" and "impact assessment" broadly and interchangeably. In exploring the interface between psychological perception research and professional visual landscape management practices, this research specifically questions the boundaries between these various approaches. Palmer [13] notes that the goals of environmental perception research are distinct from but related to the goals of visual impact assessments. While the former is typically a type of fundamental research exploring the human experience of landscape, the latter measures and evaluates particular scenes' potential impact from proposed landscape projects or management strategies.

As such, this paper argues that landscape assessment methods stand to gain from emerging research in viewing behavior and other physiological responses as objective measures of previously considered "subjective" visual landscape experiences. In particular, eye tracking in 3D immersive environments offers an opportunity to analyze observation patterns in direct response to dynamic visual landscapes. We argue that eye-tracking analysis can help bridge the gap between objectivist and subjectivist approaches to visual landscape quality by collecting and analyzing data about viewers' observation patterns (i.e., viewing behaviors), a key gap in current methodologies (Figure 1). We hope that by implementing this approach, visual quality and impact assessments may become more valid, more defensible, and faster. Furthermore, quantitatively connecting objectivist and subjectivist methods may create methods that provide a more equitable balance between professional land use guidance and public landscape preferences.

In order to integrate psychological perception and visual resource practices, however, the methods, data types, and goals of each field must be assessed for their potential compatibility. This paper is a first step in that comparison by presenting a brief overview of eye-tracking methods along with a conceptualized workflow for integrating the field with more traditional spatial analysis. The novelty and value of this contribution lie in the movement towards a more holistic understanding of the interplay between landscape spatial metrics, the spatial properties of perceptual mechanisms mediating the interaction between viewer and landscape, and psychological phenomena such as spatial cognition and landscape preference.

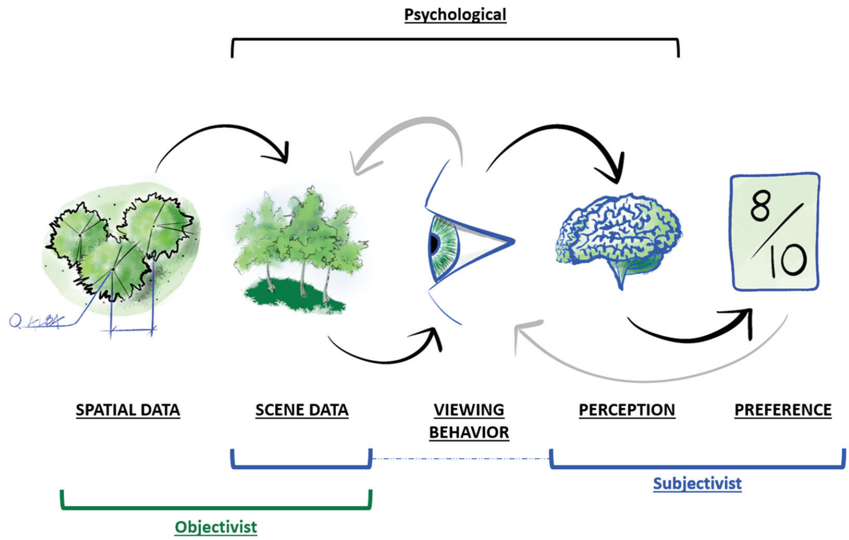

Figure 1. Conceptual diagram demonstrating the flow of information during landscape preference formation. Environmental spatial data determine scene characteristics, which are visually sampled by viewing behaviors. The raw visual data are processed by the perceptual components of the nervous system, interpreted, and then yield visual preferences. These preferences may, in turn, influence viewing behavior to resample the scene characteristics. Objectivist approaches to visual quality and impact assessment tend to focus on spatial data and scene characteristics, while subjectivist approaches historically focus on scene characteristics, perception, and preferences. A psychological approach provides methods to bridge the resulting gap through eye tracking.

2. A Brief Overview of Eye Tracking

To assess the value of eye tracking in visual landscape studies, we will first describe the fundamental aspects of eye tracking. Through vision, humans can detect relationships between spatial elements and semantic themes in environments [14] but often cannot explicitly identify how or why this is performed. Relationships between visual variables such as color, luminance, texture, parallax, and perspective all influence the visual perception system detecting these changes. There are techniques to measure these relationships objectively, but these relationships still need to be associated with semantic meaning to understand perception beyond simple sensation [15,16]. To accomplish this, research can consider the set of eye movements as a storyline between meaning, perception, and the environment. These eye movements are highly distinct among individuals based on their behaviors, experiences, tasks, and cognitive states [17]. However, as a population, we are influenced by the different environmental variables with some degree of similarity, which can result in a more structured, empirical, and—importantly—potentially predictable conceptualization of space. For example, pedestrians crossing a bridge may each have a distinct visual experience based on their unique spatial positions, interests and goals, and optical abilities, but to cross the bridge in the first place, they must all share a basic understanding of the bridge's spatial position and orientation.

As such, eye movements directly relate to a significant portion of the environmental data an individual collects and responds to during navigation [18]. Given eye movements' significant connection to spatial cognition, eye movements may have similar relationships with an individual's evaluation of, or preference for, visual landscapes. Prior research supports this hypothesis. Of particular interest, Zhou et al. [19] found that some eye movements were significantly associated with particular types of preferences, but in some cases, the same eye movement patterns were associated with opposite preferences. This finding suggests that while some eye movements may be more common with certain preference types, some eye movement patterns may be more closely related to the visual task being conducted, such as searching or evaluation. A deeper understanding of the eye movements and viewing behaviors associated with different cognitive tasks is crucial for parsing these differences and could lead to more useful eye movement-based assessments of landscape characters or scenery.

In most modern eye tracking, a set of cameras produces a range of metrics based on scene reflections off different layers of the cornea or the relative size and orientation of the eye's anatomy, such as the iris, pupil, or sclera [20]. Combining data about the speed, position, and size of the pupil can produce information about the viewer's gaze direction, cognitive load (i.e., mental effort), viewing behavior, etc. [21,22]. These data can then be combined with the environment's spatial data to map specifically viewed locations in 3D space [23]. With commercially available equipment, data can be collected at frequencies over sixty times per second and can produce a massive series of data about a viewed scene. Useful output metrics from these practices include fixations (locations or objects that are visually processed) and saccades (large eye movements between fixations), the patterns of which can be analyzed in the context of cognitive tasks and events. These data can then be clustered to reveal areas of interest (AOIs), heat maps, and scan paths (the sequential route between fixations in a 3D space) based on the spatial and temporal distribution of gaze locations in the viewer's environment. AOIs describe semantically labeled zones within a field of view or associated with objects. Heat maps can provide an overlay that communicates the frequency of fixation per unit area in a scene. Finally, scan paths examine directions, frequencies, and distances between gaze point movements during an experiment [21]. Together, this paradigm of eye-tracking research has linked gaze behavior to cognitive events and locomotion, and associated advances in human–computer interaction have led to gaze-controlled communication systems, prosthetics, and other medical assistive devices and treatments [24].

3. Leverage Eye Tracking in 3D Immersive Environments

The subjectivity of landscape ratings often obscures the latent variable of esthetic preferences [7]. Today, however, techniques in spatial analysis and scene statistics (quantitative measures of a scene's visual properties) offer the ability to quantify landscapes and scenes in new ways, particularly with the evolution of computer vision [25]. Singular landscape photographs are a mostly reliable landscape representation method with significant exceptions [5], but integrating newer cognitive and behavioral measures requires an understanding of the relationship between scenes and their spatial relationships. Without spatial data, a comparison of scenes and preferences lacks a critical component because visual stimuli are perceptually ambiguous, meaning a given visual perception may either lack clear meaning, be interpreted in multiple ways, or be generated by different stimuli.

These spatial data can be difficult to capture in practice. Collecting precise spatial data for individual scenes requires either LiDAR scans of the exact scene pictured or raster calculations, such as viewsheds or visual magnitude, based on the observation point and high-resolution digital elevation models. This method can capture spatial data for individual observation points or routes [26], but applying that data collection to a dynamic, real-world environment becomes challenging. Additionally, random elements and events in the real world add an abundance of uncontrolled elements to such an experiment. In contrast, immersive virtual reality technologies offer the ability to create controlled environments with known and easily recorded spatial and temporal data. The trade-off in these contexts is that real-world experiments gain external validity, whereas immersive VE experiments have higher internal validity. As such, real-world experiments may provide more descriptive, generalizable results with limited ability to draw conclusions about causation, while immersive VE experiments are likely to generate more precise results with a strong capacity to draw conclusions about causation, although the generalizability of the results is more restricted.

4. Integrating Spatial Analysis and Eye-Tracking Data

Recently, landscape researchers have incorporated eye tracking into studies of landscape esthetics, safety, psychology, and education [27]. Particularly relevant for landscape architects and associated professionals, Dupont et al. [28–30] have produced a robust research agenda using eye tracking to evaluate between-subject and within-subject differences in gaze behavior across multiple landscape scenarios. Specifically, Dupont's research program found that gaze behavior varied significantly when the type of photograph used in landscape assessment surveys was changed and when the homogeneity and enclosure of the pictured landscape were manipulated as well [28]. Dupont et al. [29] further proposed a "saliency map" to predict subjects' areas of interest within landscape photographs based on differing elements [30]. Overall, Dupont's research program indicates that media format, scene composition, semantic meanings, and design features such as style and color influence how individuals look at landscapes.

In general, eye tracking presents several advantages for landscape assessment research. For instance, eye-tracking measurements provide a robust, objective measure of a viewer's interaction with a visual stimulus such as a landscape. These quantifiable behavior metrics can then be correlated with subjective landscape ratings, quantified landscape features can be used to predict areas of interest, or group-level differences can be determined in viewing patterns. Semantic preferences and legibility can also be inferred from visual behavior, and, in combination with physiological metrics such as skin conductivity, affective arousal can be inferred and related to visual experiences [8]. Given the prevalence of visibility-based concerns around renewable energy development, understanding visual experiences around these developments will be vital in addressing community concerns. Such research could also differentiate between visibility concerns and misattributed social concerns that may receive less attention in the renewable energy development process [31,32].

These advantages address a need in the field of landscape esthetics for increasingly valid and objective assessment practices, as described by Daniel [1]. Currently, several GIS tools offer quantitative landscape assessment methods [33], but these are often focused on the data manipulation and visualization domains of spatial analysis. Several studies expand into quantitative spatial analyses of landscapes' visibility, land use, and landform [34], and another study even maps crowdsourced landscape preferences from surveys or web-based photo-sharing platforms [35]. However, these methods do not provide a means to associate the behavioral processes of observation with the rationale for the different measures or ratings. In basic research, good peer review always asks, "How was this data collected?" to examine potential biases in the collection process; applying the same question to individuals' visual landscape preferences offers a chance to parse visual preferences and account for an individual's perceptual biases. Eye-tracking data are fundamentally spatiotemporal and may include an observer's position, their point of regard (where they are looking in the environment), geographic coordinates in space for both, and a time stamp. The point of regard may be associated with quantitative metrics and qualitative features at its location, such as an object's semantic meaning or unique texture, color, brightness, and other elements used in the objectivist paradigm of visual impact assessment. Points of regard, along with their temporal qualities and attributes, can then be input into a GIS and used to facilitate empirical validation of GIS-based impact assessment tools. Additionally, scan paths can also be integrated within GIS, allowing for the quantification of areas of interest in terms of physical or visual scope as well as time spent looking at each one. While GIS is well suited to measure and produce visualizations of eye-tracking data, a GIS is not strictly necessary to analyze these data. Spatial analysis with GIS is not currently a standard practice when analyzing eye-tracking data. However, spatial analysis offers new opportunities for eye-tracking analysis.

To describe these opportunities, Figure 2 adapts Orquin and Holmqvist's [36] workflow for eye-tracking analysis and Unwin's [37] categories of spatial analysis to visualize how these distinct processes and data products can interact. In Orquin and Holmqvist's [36] approach, appropriately collected and cleaned eye-tracking data go through a series of analytic steps, beginning with clustering the raw data into fixations and saccades. This step identifies which tracking frames are most likely to coincide with active visual processing. Spatial coordinates for raw data points can be retained at this stage or averaged across clusters to simplify the data set. At this point, the clustered data are sufficient for mapping through spatial data manipulation, the first of Unwin's spatial data analysis categories, which also include spatial statistics, exploratory data analysis, and spatial modeling [37]. Unwin's categories correspond to goals focused on mapping, describing, analyzing, and predicting. In the proposed workflow, eye-tracking data at any level can be spatially analyzed as long as it retains its spatial coordinates throughout the data management and analysis processes. In this process, the spatial coordinates of the viewer can be just as important as the coordinates of their fixations and saccades. This distinction between viewer and viewed positions allows for the examination of the impact of individual elements within the scene over the course of an experiment, as well as analyses of how viewing behaviors change with respect to viewer position.

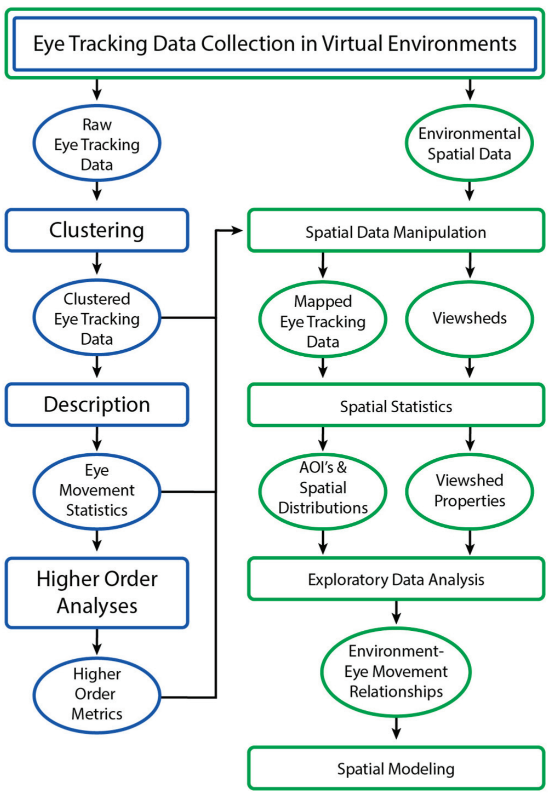

Figure 2. Orquin and Holmqvist's [37] workflow clusters statistically describe and analyze eye-tracking data. These analysis products can be tied to their respective spatial coordinates, mapped, and analyzed for relationships with viewshed properties, leading to the potential for predictive spatial modeling of environmental impacts on observers' viewing behavior.

Traditional eye-tracking analyses are often conducted using 2D stimuli (e.g., photos), but some of the core metrics, such as AOIs, also apply to 3D spaces. Spatial analysis, often performed using GIS, has the distinct advantage of incorporating 3D quantitative environmental elements (e.g., topography and user movement) into the evaluation, allowing for a richer, more context-sensitive understanding. Tools like ArcGIS offer basic functions for spatial analysis, while advanced statistical tools (e.g., R) can provide a range of additional measures. Regardless of the analytical technique, the primary strength of spatial analysis lies in its ability to offer comprehensive viewshed descriptions, providing a depth of environmental context that traditional analyses typically lack. So, not only can we develop fine-grained measures, such as total dwell time on a specific object, but we can also develop powerful global measures, such as hotspot maps and viewing extents, to provide a more holistic, objective measure of landscape perception. These environmental metrics add important context to the behavioral and physiological data by describing not only what is seen but also the setting in which something is seen, which has been shown to influence viewing behavior and preferences [8,28].

5. Discussion

Following the existing typology of landscape assessments, eye tracking could be used in surveys or perceptual preference evaluations. In surveys, eye tracking could be used to gauge the distribution of fixations within landscapes and across groups. Such distributions could be used to measure the relative importance of distinct landscape features between groups and would necessitate the description of viewer populations as part of a visual inventory. In preference evaluations, eye tracking could potentially serve as a tool for standardizing individuals' disparate preference scales (see Daniel's Scenic Beauty Estimation Method) for specific elements by weighting ratings according to the amount and type of visual attention they receive.

Integrating eye-tracking data with traditional methods such as surveys and scenic beauty estimation allows for a multifaceted approach to visual quality assessments. Eye tracking can validate or challenge the results obtained from more conventional methods, offering a way to cross-check for reliability and accuracy. This would allow practitioners to compare how observational patterns might change in response to changes in infrastructure (e.g., wind turbine, gas, or oil pump). For example, Zhou et al. [19] found significant differences in related eye movement metrics for different categories of landscape elements, such as waterscapes or facilities, although further research is necessary to replicate these findings. On the other hand, if the patterns remain stable while ratings change, it would motivate more studies on landscape interpretations. For example, if a participant highly rates a landscape and then lowers their rating after the installation of a wind turbine, we can then measure the relationship between changes in observational patterns and changes in landscape ratings. The eye-tracking data can then be assessed alongside feelings of comfort, attraction, pleasure, and curiosity as a suite of variables feeding into final ratings. Eye tracking could help researchers better understand how to measure observational patterns and their interrelationship with emotional responses. Thus, combining ratings, preference surveys, and eye tracking may improve how experts conduct their assessments and create visual impact mitigation strategies.

Eye tracking also offers another means to explore unconscious and physiological responses to elements of visual landscape experiences. While eye tracking can provide attentional metrics about viewing behavior, these could also be coupled with physiological responses and stated preferences. This approach could be applied to key observation points, recreational routes, or urban settings. Once again, data about the specific elements and observational behaviors can be leveraged to understand their association with stress and restoration rather than relying on broader global statistics (e.g., topography, greenspace). We might further investigate the role of spatial cognition in visual landscape preferences and integrate components of viewing behavior, physiology, and spatial metrics.

Further, eye tracking allows for descriptions of group-level differences in observation patterns. These differences may stem from different expectations about a landscape's contents as well as differences in the relative salience of environmental features to each viewer. Since each individual has a different visual experience of the same landscape, knowing what elements they viewed, in what order, and for how long may provide significant insight into the raw data underpinning their eventual landscape rating. These differences may also imply unconscious preference ratings and may help compare public and professional assessments.

6. Conclusions

Eye-tracking research offers a bridge between existing objectivist and subjectivist landscape assessment methods by bringing observational patterns—a critical link between scene metrics and viewers' perceptions—into the research agenda. While eye tracking may eventually contribute directly to the practice of visual quality or impact assessments, the near-term benefits of this work will most likely center around contributing to the objectivity and defensibility of assessments through validation and methodological recommendations. The ongoing integration of eye-tracking research with spatial analytics also offers a promising avenue for refining existing viewshed metrics and creating new methods for exploring the spatial properties of visual experiences. In particular, exploratory spatial analyses may provide us with greater insight into the role of geographic variables in shaping observation patterns, perceptions, and subsequent preference ratings.

This paper provides the next step toward quantifying cumulative visual impacts as objective behavioral and physiological responses. This can help strengthen the defensibility of our assessments and increase the generalizability of our results. Accomplishing both of these will require a more data-driven approach to understanding the perceptual processes involved in perceiving and interpreting visual landscape changes, and eye tracking can provide rich data capturing behavioral indicators of those processes.

The most immediate limitation of this work is its current conceptual nature. As noted, the fields of eye tracking, landscape perception, and landscape or impact assessments are well established, but their effective integration has received limited attention. Future eye-tracking research should explore the role of viewing behaviors in the distinct realms of landscape perception, landscape character assessment, and visual impact assessment to further identify the most appropriate and beneficial applications of eye-tracking techniques.

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Using a Public Preference Questionnaire and Eye Movement Heat Maps to Identify the Visual Quality of Rural Landscapes in Southwestern Guizhou, China

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Abstract: Rural landscapes serve as important platforms to determine the landscape characteristics (LCs) of rural areas, demonstrating the landscape characteristics specific to certain regions to the public. However, the development trend of urban and rural areas is continuous and impacts the characteristics of rural landscapes, which directly affects the public's visual experience and landscape perception. In order to improve the characteristics of rural landscapes, this study evaluates and analyzes their visual quality based on public preferences and eye movement heat maps. The results show that most subjects have a high preference for horizontal, open-view rural landscapes with fields and landform features as the dominant landscape elements. This study also found that the combination of strip-like or planar settlement buildings with regional characteristics and landform features has an active impact on the visual quality of rural landscapes. These results show that rural landscapes characterized by scattered settlement buildings without significant regional characteristics, horizontally curved roads, bridges, and other human-made landscape elements, and mixed and disorderly vegetation have low landscape preference, which degrades their visual quality. These research results provide crucial suggestions for landscape managers to protect and renew rural landscape features.

Keywords: rural landscape; southwest Guizhou region of China; landscape character; landscape visual quality; public preference

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1. Introduction

1.1. Research on Rural Landscape Characteristics

"Rural" as a regional concept refers to all areas except urbanized areas and primitive no-man's land [1]. In 1992, the World Heritage Committee added cultural landscapes to the "Operational Guidelines", allowing these landscapes to be included in the "World Heritage List". The "Convention for the Protection of the World Cultural and Natural Heritage" became the first international legal instrument to recognize and protect cultural landscapes; these include three subcategories [2], and rural landscapes belong to the "organically evolved, continuously evolving landscape" subcategory. Rural landscapes, especially those transformed by humans, are typical cultural landscapes. They represent cultural heritage and "the joint work of humankind and nature" [3].

Rural areas are continuously evolving landscapes, and most rural areas are still undergoing continuous development and change [4]. Rural landscape elements represent the material basis of rural landscape composition and determine the contextual characteristics of the landscape environment [5]. Rural landscape features are characteristic patterns shaped by specific natural, architectural, and cultural elements, and have clear and consistent external physical representations [6]. Changes in the original characteristics of the rural natural environment and landscape, if not properly managed and controlled, will result in a decline in the visual quality of the rural landscape [7].

However, while rural landscape engineering projects improve production and living conditions because they all follow the same set of standards and lack ecological landscape construction theory and technical guidance [8], rural landscape construction ignores regional differences and suppresses local flavor and regional characteristics; in addition, over the past few decades, with the rapid development of society and urban expansion, the landscape in rural areas has been gradually changed and threatened by ecological damage and environmental pollution, and the service functions of rural ecosystems have been severely limited [9]. On the other hand, rural tourism has undergone unprecedented development, and the countryside has gradually become the most popular type of tourist destination among urban residents for leisure and recreation [10]. It is clear that rural landscapes are currently facing conflicting problems. They must not only resist the homogenization of landscape features and the destruction of ecological and visual environments, but also possess regional characteristics that make them attractive tourism destinations.

1.2. Literature Review

1.2.1. Landscape Characteristics and Their Evaluation

Landscape characteristics are defined as "unique, recognizable, and consistent patterns of elements in a landscape that make one landscape different from another, rather than better or worse" [11]. Different elements in a landscape are independent of each other, and their combination to form a unique scene give the landscape its so-called "character" [12]. Landscape elements are individual features in the landscape that can be spatially delineated [13]. They are combined with land cover and land use to form landscape patterns, which dictate the characteristics [14] and functions of the area [15].

Research on Landscape Character Assessment (LCA) began in the UK to improve the accuracy of the character description process (including the identification, classification, and zoning of features) and provide technical support for spatial decision-making [11]. Landscape Character Assessment is considered a tool for the dynamic management of regional characteristics [16]. Landscape changes considerably affect the visual aspects of a landscape [17], and landscape features, which can be used to quantitatively describe and identify scenes, can be used to further measure human preferences and improve visual quality [18]. Yuncai Wang et al. [5] reviewed the literature on the evaluation of rural landscape characteristics and summarized five types of characteristic evaluation indicators, namely landscape elements (climate, terrain, soil, vegetation, water bodies, farmland, buildings, etc.), morphology (landscape pattern index, etc.), and functional (land use, openness, convenience, comfort, etc.), visual (openness, uniqueness, orderliness, coordination, neatness, etc.), and socioeconomic indicators (population density, the proportion of the population engaged in agricultural production, the proportion of income from tourism in villages and towns, etc.). In their research on landscape perception and evaluation, Tveit et al. [19] identified nine key visual concepts (management, history, coherence, interference, visual scale, complexity, imageability, naturalness, and ephemerality) and proposed a four-level framework related to visual feature assessment: concepts > dimensions > landscape attributes > indicators. Their identification of visual features is consistent with ELC and has been put to use in several studies [20,21]. The evaluation and analysis of rural landscape characteristics in this study is based on the elements of rural landscapes and the visual quality of spatial scenes.

1.2.2. Landscape Perception and Visual Quality

In this study, we assess public landscape perception in various spatial scenes of rural landscapes through a multi-angle depiction of environmental perception. Landscape spatial perception can be divided into two categories: physical perception (vision, hearing, touch, smell) and psychological perception (preference, psychological feelings) [5]. In this study, physical perception is based on visual observation, with existing research showing that "more than 80% of all external things that humans obtain come from vision" [22], while psychological perception pertains to differences in the public's rural landscape preferences based on psychological feelings.

Theories on the relationship between perception and preference include the biophilia hypothesis proposed by Wilson in 1984 [23], the Gestalt principle of visual perception proposed by Kovka et al. [24], and the prospect–refuge theory proposed by Appleton in 1975 [25]. However, the most widely used is the perception model proposed by Kaplan in 1989 [26]. It contains four information variables (mystery, complexity, readability, and coherence) [27] that are predictors of environmental preferences, among which complexity represents the content of the scene. The diversity, richness, and coherence of a landscape's elements impact the public's interest in the landscape. The unity and coherence of each landscape element in terms of shape, size, and texture determine the land use and nature of a region [26]. While there is an element of mystery in a scene with a hidden message [28], more information can be learned when there is consistency between conditions and by walking into the scene.

The visual quality of a landscape is determined by assessing the relationships between the impacts of landscape objects' physical attributes on human perception [29], and the public's visual landscape preferences are considered for the psychological evaluation of human–environment interactions [30]. At the same time, the visual quality of a landscape is considered synonymous with its esthetic value. These can be tested based on public evaluation or objective characteristics. Existing research has proven that assessing the public perception of landscapes is an important step towards sustainable management [31,32].

In recent decades, China's rapid urbanization and industrialization have promoted tremendous changes in the structure of the rural agricultural industry, farming production methods, spatial organization, and rural living environments [33]. Rural development has entered a new stage of transformation and agricultural modernization. The adjustment of agricultural structure in rural areas will inevitably lead to the reconstruction of rural landscapes, economies, and societies. Landscape features and functions are undergoing a transformation from production spaces to consumption spaces. Urban fringe areas and villages with advantages in terms of land and environmental resources are continuing to use agriculture. To promote changes in rural landscapes, increase economic income, and improve the quality of human settlements to achieve optimal life satisfaction, it is necessary to adjust the structure of the agricultural sector and choose different planting types [34]. Over the past decade, China has been making efforts to improve rural life and the economy by reassessing land use [35]. In academia, research has focused on the impacts of rural land use and agricultural transformation on rural landscape patterns and functions, classification and evaluation, tourism and rural landscape planning, optimization and reconstruction, management, development models, and other aspects [36–40], as well as in-depth analyses of agricultural structural transformation's impacts on rural landscapes and residents' life satisfaction [41]. At the same time, the protection of traditional rural landscapes is not only affected by exogenous driving factors such as top-down policies and tourism, but also by endogenous driving factors originating from rural social and cultural backgrounds, including social and cultural vitality. There is a strong positive correlation with the integrity of traditional rural landscapes; compared with exogenous driving factors (top–down regulatory policies and tourism development), endogenous driving factors (i.e., the connection between people and the environment) have a greater impact on residents' commitment to the protection of traditional rural landscapes, and cognition, intention, and behavior have a more pervasive and positive impact [42].

In China, since the 19th National Congress of the Communist Party of China, rural revitalization has become a contemporary focus. At the same time, cultural tourism plays an important role in rural revitalization. Rural landscapes are important rural tourism destinations and can reflect the unique characteristics of a region. They not only allow tourists to experience the local rural style or culture, but can also induce a "love affair" with the rural landscape. Therefore, the visual quality of rural landscapes has become an important factor affecting the visitor experience. However, among the studies on rural revitalization in China, only a few have focused on the impact of the visual dimension of rural landscapes on the visitor experience, resulting in a lack of understanding of its importance and the need for its protection among policymakers. Therefore, it is necessary to carry out visual evaluation research on rural landscapes. Through this type of evaluation, we can determine the "active" and "passive" areas of the landscape, and then propose relevant countermeasures to improve landscape quality and enhance landscape value or ecosystem services [43]. The purposes of this study are as follows:

(1) The classification and type identification of rural landscape features in Southwest China;
(2) Determining the public's preference for visual quality based on the rural landscape characteristics of Southwest China;
(3) Determining the landscape characteristics and population characteristics that affect rural landscape preferences in Southwest China.

2. Materials and Methods

2.1. Study Area

The study area is the countryside on the west side of the Gui'an metropolitan area in Southwest China, most of which is used for agriculture and forestry. This area has rich rural landscape features, such as plateau landforms, rural settlements, fields, vegetation, etc. (Figure 1).

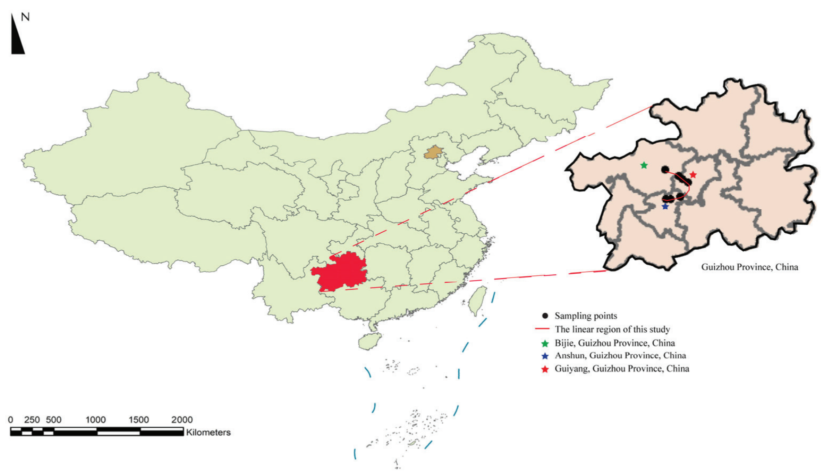

Figure 1. The location of the study area.

2.2. Study Methods

The theory of landscape perception states that there is an interactive relationship between the public and the landscape. The public is the subject of perception, and the landscape is the perceived object; that is, the spatial physical characteristics and related attributes presented by the perceived object are related to the psychological feelings and preferences of the public. Among the results of this interaction, the physical characteristics of the space are one of the most important factors affecting the visual quality of the landscape. The unique plateau landforms in Southwest China and the rural settlements built on these natural landforms collectively demonstrate the style of the regional rural landscape. However, rural landscapes are composed of natural and artificial landscape elements, and some artificial elements have a certain negative impact on the public's visual satisfaction [44]. Therefore, based on the landscape preference theory, this study proposes taking the public as the evaluation subject of landscape visual quality, and uses a Likert scale to determine the public's preference for rural landscapes. The Likert scale is a widely used tool in social science research for measuring attitudes [45]. Upon establishing a bipolar scale, subjects were asked to select a value that expressed their assessment of the visual quality of a series of rural landscape pictures.

Eye movement heat map: People's preferences for landscapes are closely related to their visual observation behavior [46]; based on this, our study used an eye-tracking device to record eye movement heat maps generated based on the visual behavior of the subjects. This allowed us to determine the areas of the pictures where the subjects' visual attention was focused. This intuitively revealed the different landscape elements that the subjects were drawn to. We then characterized what types of landscape features and elements had a visual impact on the subjects. Specifically, pictures obtained on site were used as stimuli to awaken the subjects' "landscape sense" through representative sample scenes [47,48] and to identify the public's perception of the visual quality of rural landscape spatial characteristics as well as the landscape elements that they were drawn to.

2.3. The First Step

Material collection: During a high-speed train journey, a Go-Pro 9 camera was used to record images of the area, and a picture was extracted from the collected image material every 2 s to ensure that the extracted pictures covered all of the rural landscape features in the study area. A final number of 60 rural landscape feature pictures were extracted using this method.

Landscape feature identification in rural areas of southwestern Guizhou: This study classified the landscape characteristics of the extracted images based on landforms, land use types, vegetation, human-made structures, etc., and finally determined twelve categories. Each category contained five images of the same type, for a total of sixty images (See Appendix A). Upper-case LC was used as the code, and the numbers after the code represent each type of landform. LC-1 represents a "field landscape surrounded by mountains". For the sake of our scientific research, there were at least 5 pictures of each type of landscape feature, numbered LC-1-1, LC-1-2, LC-1-3, . . . LC-1-5. Table 1 shows a picture of each type with its code and label.

Table 1. Each group with their LCs.

Group	Landscape Character	Code	Photo Example
A	Field landscape surrounded by mountains	LC-1-1	
B	Natural landforms, fields, and settlement landscapes	LC-2-1	
C	Plateau landforms and roadside strip settlement buildings	LC-3-1	

Table 1. *Cont.*

Group	Landscape Character	Code	Photo Example
D	Plateau landforms and scattered settlement buildings	LC-4-1	
E	Settlement and landscape	LC-5-1	
F	Fields and landform landscape	LC-6-1	
G	Plateau landform settlements and winding rural roads	LC-7-1	
H	Viaduct connecting mountains	LC-8-1	
I	Plateau landform natural landscape	LC-9-1	
J	Field and settlement landscape	LC-10-1	

Table 1. *Cont.*

Group	Landscape Character	Code	Photo Example
K	Settlement and plant landscape	LC-11-1	
L	Field landscape	LC-12-1	

2.4. The Second Step

Questionnaire and eye movement experiment: The present study first used a questionnaire scale to identify the rural landscape space, determined the visual quality status of the landscape space through a subjective method, and then used eye movements to identify the areas that the subjects were focused on. Research conducted by Lappi shows that data recorded by an eye tracker can tell us what subjects see, but not how they felt when watching [49]. Therefore, this study combined a questionnaire with the eye movement experiment, thereby enabling a more accurate and comprehensive visual quality assessment of rural landscape features.

The first stage of this study was the questionnaire survey, which consisted of two steps. Step A comprised basic information on the subjects who filled in the questionnaire, including their gender, age, education, type of work, location, frequency of going to the countryside, etc.; 8 items that are closely related to this study; and question items. Step B was a picture survey using the Likert scale, whereby subjects were invited to view and rate each rural landscape scene picture, with scores ranging from −2 to 2. Passive numbers represent passive rural landscape scenes, and active numbers represent active rural landscape scenes. The degrees of expression were as follows: −2—dislike the scene the most, −1—dislike the scene, 0—neutral, 1—like the scene, 2—favorite scene (Figure 2). Wartmann effectively verified that the Likert scale method can be used to determine the factors that affect visual quality as perceived by the public [50]. Mundher et al. [51] and Hangyu Gao et al. [52] used a Likert scale to divide landscape characteristics into two groups: active and passive.

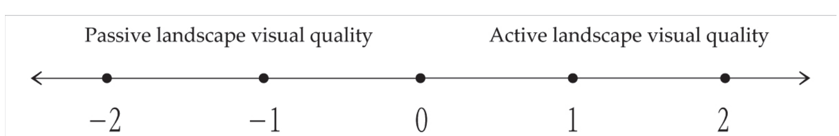

Figure 2. Likert scale used in this study.

The second stage of this study was the eye-tracking experiment, which involved subjects viewing rural landscape pictures. The subjects sat in front of the eye-tracking equipment monitor, with the distance between their eyes and the monitor screen kept at 70-80 cm, and visual calibration was performed. Afterwards, the subjects viewed the experimental samples for 5 s each. The pictures with the participants' preferred landscape elements circled were collected and processed to obtain a hand-drawn heat map, which was used to analyze and identify the landscape features that affect the visual quality of the landscape.

This survey was carried out from September to October 2023, and a total of 246 valid questionnaires and pictures of participants' landscape feature preferences were collected. SPSS 27.0 was used to analyze the questionnaire data. At the same time, Begaze software (Version 3.2) in combination with the eye tracker was used to generate a heat map of the subjects' focus; in addition, the regional ranges of different landscape elements in each map were drawn separately in ArcMap 10.7 (Figure 3) to facilitate the analysis and statistics.

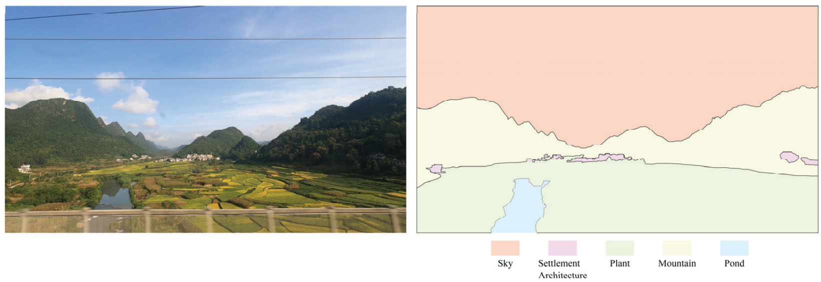

Figure 3. Classification of landscape elements in the scene.

3. Results

3.1. Demographic Description

As shown in Table 2, 246 participants completed the questionnaire, including 131 women, accounting for 53.26%, and 115 men, accounting for 46.74%. Regarding age groups, most of the participants were under 26, and there were 125 people between 27 and 35 years old, accounting for 50.81%. In terms of education level, 202 respondents had received higher education, including 156 undergraduates, accounting for 63.42%, and 46 graduate students and above, accounting for 18.70%. A total of 64.23% (n = 158) of the respondents lived in cities, and there was one respondent who had lived there for less than a year; however, only forty-three respondents had been to rural areas in southwestern Guizhou, accounting for 17.48%, and only 6.3% (n = 15) had never been to rural areas. To summarize, the respondents were mostly female, highly educated, and non-local individuals living in cities. They had a certain understanding of and familiarity with the countryside, but had limited knowledge of the study area.

Table 2. Questionnaire demographic data.

Item	Category	Frequency N	Percent %
Place of residence	Urban area	158	64.23%
	Suburban area	62	25.20%
	Rural area	26	10.57%
Gender	Male	115	46.74%
	Female	131	53.26%
Age	18 to 25	53	21.54%
	26 to 35	125	50.81%
	36 to 45	37	15.04%
	46 to 55	19	5.69%
	Above 55	12	6.91%

Table 2. *Cont.*

Item	Category	Frequency N	Percent %
Education level	Junior high school or below	3	1.22%
	Junior high school	6	2.44%
	High school	35	14.23%
	Bachelor's degree	156	63.42%
	Master's degree or higher	46	18.70%
Type of work	Student	48	19.51%
	Self-employed	102	41.46%
	Private sector employee	73	29.67%
	Government department employee	23	9.35%
Has previously visited Gui'an metropolitan area	Yes	43	17.48%
	No	203	82.52%
Resident	Yes	31	12.60%
	No	215	87.39%
Frequency of visits to rural areas	Less than one a year	15	6.10%
	2 times a year	180	73.17%
	3 to 5 times a year	45	18.29%
	More than 5 times a year	6	2.43%

3.2. Photo Survey

The landscape pictures selected in this study were measured using a five-point Likert scale ranging from -2 to 2. Based on this standard, the average value of landscape visual quality was obtained after the 60 pictures of the questionnaire were ranked according to their scores (Table 3). Among them, the number of pictures representing active landscape visual quality (N = 29) was slightly lower than the number of pictures representing passive landscape visual quality (N = 31). The absolute average values of active and passive landscape visual quality pictures are not greater than 1. The highest score for active landscape visual quality pictures is 0.87, and the lowest score for passive landscape visual quality pictures is -0.64. These results show that the respondents' overall visual perception of the rural landscape is within an acceptable range, indicating that people are generally satisfied with the overall rural landscape. Subsequently, according to the subjects' ratings of the rural landscape pictures (Table A1), the pictures with the top six active and passive landscape visual quality scores, namely LC-6-3, LC-1-2, LC-9-4, LC-3-2, LC-3-3, and LC-3-5 (active landscape visual quality pictures) and LC-7-2, LC-8-4, LC-4-3, LC-4-4, and LC-4-5 (passive landscape visual quality pictures), were selected and an overall analysis of landscape visual quality trends was conducted.

It can be seen from Table A1 that in the active landscape visual quality group, the six pictures selected come from four groups; three are from group 3 (LC-3-2 = 0.68, LC-3-3 = 0.66, LC-3-5 = 0.64), showing the landscape characteristics of "plateau landforms and roadside strip settlement buildings", and the other three are from group 6, group 1, and group 9. The common feature of these three groups is that natural landform features form the background of landscape space and occupy the main part of the picture. At the same time, the proportion of the landscape spatial composition is coordinated. However, in the passive landscape visual quality group, the six selected pictures come from four groups, with the "plateau landform settlements and curved rural roads" group having the worst visual quality; however, most of the photos have active landscape visual quality. Similar landscape features in the quality group, especially group 4, lack effective landscape management, resulting in the foreground vegetation elements being too messy and disordered. At the same time, there is a lack of effective interaction between the dominant landscape elements, represented by mountains and settlement buildings, in the scene. The transition and connection cause a fragmentation in visual perception, resulting in a significant reduction in the subjects' preference for landscapes.

Table 3. Images sorted by average rating.

Active Landscape Visual Quality			Passive Landscape Visual Quality		
No.	**Photo Codes**	**Mean Value**	**No.**	**Photo Codes**	**Mean Value**
1	LC-6-3	0.87	1	LC-7-2	−0.64
2	LC-1-2	0.83	2	LC-8-4	−0.57
3	LC-9-4	0.79	3	LC-4-3	−0.48
4	LC-3-2	0.68	4	LC-4-4	−0.39
5	LC-3-3	0.66	5	LC-4-5	−0.33
6	LC-3-5	0.64	6	LC-12-2	−0.28
7	LC-1-3	0.63	7	LC-7-1	−0.26
8	LC-6-2	0.61	8	LC-7-5	−0.25
9	LC-6-1	0.57	9	LC-8-1	−0.21
10	LC-9-5	0.55	10	LC-7-3	−0.18
11	LC-6-5	0.53	11	LC-8-5	−0.18
12	LC-1-5	0.51	12	LC-12-3	−0.18
13	LC-9-3	0.48	13	LC-8-2	−0.15
14	LC-6-4	0.45	14	LC-12-5	−0.12
15	LC-1-4	0.42	15	LC-8-3	−0.11
16	LC-4-2	0.04	16	LC-12-1	−0.11
17	LC-2-5	0.38	17	LC-10-5	−0.11
18	LC-9-1	0.36	18	LC-10-2	−0.08
19	LC-2-3	0.33	19	LC-12-4	−0.06
20	LC-5-5	0.26	20	LC-4-1	−0.05
21	LC-9-2	0.25	21	LC-10-4	−0.05
22	LC-2-2	0.24	22	LC-11-2	−0.04
23	LC-3-1	0.22	23	LC-11-5	−0.04
24	LC-1-1	0.18	24	LC-7-4	−0.03
25	LC-2-1	0.18	25	LC-11-4	−0.03
26	LC-2-4	0.15	26	LC-10-3	−0.02
27	LC-5-2	0.12	27	LC-11-3	−0.02
28	LC-5-1	0.08	28	LC-5-4	−0.02
29	LC-10-1	0.01	29	LC-3-4	−0.01
			30	LC-5-3	−0.01
			31	LC-11-1	−0.01

Table A2 shows the differences in average visual quality between groups. It is clear that the pictures with fields as the main landscape features are all classified in the active landscape visual quality group, except LC-12-2. On the contrary, mountains, as natural landscape elements that express regional characteristics, and different landscape features formed through a combination of different elements, have opposite visual qualities; specifically, mountains as a landscape background, when combined with water elements, show active visual quality. It can be seen that water elements are of great significance in improving the visual appeal of rural landscapes [52], and mountains alone or as the dominant landscape elements combined with artificial landscape elements, such as settlement buildings, roads, bridges, etc., were used in the assessment of passive landscape visual quality.

3.3. The Impact of Heat Maps and Landscape Features on Visual Quality Assessment

Heat maps intuitively present the areas that subjects pay attention to and the duration and intensity of focus on these areas. Red areas represent a greater preference for specific or dominant landscape elements in the scene. The subjects' preferences for landscape elements are accurately reflected in the pictures in Table A3 and the heat maps obtained after recording the subjects' attention; Table A3 includes the active and passive visual quality of the pictures provided in Table A1. In the active landscape visual quality group, the red areas of the heat maps are concentrated on fields, landforms, and settlement buildings, indicating the subjects' perception of the visual characteristics of these three types of landscape elements. They show a high preference for landscapes, although some plants are also in the red area, and the intensity of attention is slightly lower than that paid to fields, landforms, and settlement buildings. At the same time, from the perspective of landscape spatial composition, active visual quality pictures show open-space scenes. The outlines of different types of landscape elements in these spaces are clear, the number of landscape elements is moderate, and the area of each element in the space is moderate; this highlights that the dominant elements and those with distinctive characteristics in the landscape space make the visual experience of the space holistic and provide a sense of coordination.

In the passive landscape visual quality group, except for group 12 (field landscape), all groups lack field landscapes as the dominant elements in the space. The areas that subjects pay attention to are relatively scattered, but the landscape elements they pay attention to are more natural elements, such as the mountains and the sky. There are relatively few settlement buildings. On the one hand, the proportion of settlement building areas in these images is small, and on the other, humans have an innate preference for natural elements [53]. This is similar to the results of the active group. However, due to the influence of spatial composition in images in group 8, the bridge connecting the mountains becomes a focal landscape element that attracts visual attention because it occupies an important position in the space and spans the left and right sides. In group 12, although the dominant elements in the space are landforms and fields, there is a certain number of small features and many types of landscape elements within the field landscape which distract the subjects' visual focus; at the same time, different types of landscape elements detract from the overall sense and order of the landscape composition, making the landscape space cluttered and disorderly. From the perspective of landscape spatial composition, passive and active visual quality pictures both represent open-space scenes; thus, it is clear that the complexity and recognizability of spatial scenes will affect the visual preferences of viewers. To a certain extent, for rural landscapes, the openness of visual space is less important than the sense of order and integrity.

3.4. Related Factors That Affect Visual Quality

Based on the aforementioned mean grouping, the reliability of the active and passive visual quality of the two groups was examined separately. The results of the reliability test are more than 0.7, within the valid range of values (Table 4); the normality of the survey sample was also tested with regard to gender. Then, we determined the rationality of the analysis and research. According to the results shown in Table 5, the Kolmogorov–Smirnov significance values of the active and passive groups are both greater than 0.05 ($p > 0.05$), which indicates that the null hypothesis can be accepted. These results meet the requirements of normal distribution.

Table 4. Results of reliability statistical analysis.

Visual Quality	Valid (N)	N of Items	Reliability Cronbach's Alpha
Active Landscape Visual Quality	246	30	0.956
Passive Landscape Visual Quality	246	30	0.948
Total reliability (Cronbach's Alpha) for 60 photos			0.962

Table 5. Results of normality tests.

Group	N	Mean	Std.	Skewness	Kurtosis	Kolmogorov–Smirnov Test	
						Statistic *D*	*p*
A	246	0.837	0.202	0.036 *	−0.229	0.218	0.000 ***
C	246	0.667	0.18	0.023 *	−0.08	0.231	0.000 ***
F	246	0.869	0.223	0 ***	−0.314	0.183	0.000 ***
I	246	0.786	0.194	0.166	−0.382	0.203	0.000 ***
Active Landscape Visual Quality Group	246	0.79	0.15	−0.078	−0.438	0.099	0.000 ***
D	246	−0.403	0.118	0.004 **	−0.117	0.328	0.000 ***
G	246	−0.635	0.2	0.086	0.14	0.223	0.000 ***
H	246	−0.554	0.182	0.533	1.458	0.259	0.000 ***
L	246	−0.272	0.109	0.042 *	−0.857	0.352	0.000 ***
Passive Landscape Visual Quality Group	246	−0.466	0.123	0.412	1.011	0.096	0.000 ***

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

A *t*-test and one-way ANOVA were used for analysis. The *t*-test, as shown in Tables 6 and 7, shows that the two factors that affect active and passive visual quality are whether the subject has visited the study area before and whether the subject is a local resident. However, these effects are limited to certain groups of images of specific landscape features.

Subsequently, single-factor analysis was conducted on the data. Limited by the number of subjects, the 46–55 and above-55 age groups were combined to form an above-46 age group. One-way ANOVA was used to study the effects of the four different age groups on A, C, F, I, and P0S, as well as D, G, H, L and NEG. As shown in Table 8, participants of different ages show significance ($p > 0.05$) for I and H, which means that the four participant age groups show consistency in their assessment of both groups I and H and there is no difference between their perception of these groups; therefore, no post hoc test analysis was required. The other items affected by the four participant age groups are A (field landscape surrounded by mountains), C (plateau landform and roadside strip settlements), F (fields and landform landscape), P0S, D (plateau landforms and scattered settlement buildings), G (plateau landform settlements and winding rural roads), L (field landscape), and NEG. A total of eight items showed significance ($p < 0.05$), which means that the four groups of participants of different ages show significant differences in how they perceive A, C, F, POS, D, G, L, and NEG, which requires specific post hoc analysis.

As can be seen from Table 9, the above variance analysis found that participants of different ages showed differences in their perception of eight sample groups: A, C, F, ACT, D, G, L, and PAS. Specifically, the multiple comparison (Bonferroni) correction method was performed.

From the perspective of the active picture group, picture group A shows a significance level of 0.05 (F = 3.173, $p = 0.025$), and an obvious difference is reflected in "Age group 3 > Age group 4". Regarding the significance level of picture groups C and F, the values are

0.01 (F = 4.178, $p = 0.007$) and 0.05 (F = 3.173, $p = 0.025$). Significant differences are reflected in "Age group 2 > Age group 4".

Table 6. Visitor and non-visitor variables: *t*-test results.

Group	Variable	N	Mean	Std.	Mean Value Difference	Difference 95% CI	*t*	*df*	*p*
A	Non-visitor	203	0.82	0.2	−0.09	−0.151~−0.019	−2.549	244	0.011 *
	Visitor	43	0.91	0.21					
	Total	246	0.84	0.2					
C	Non-visitor	203	0.66	0.18	−0.03	−0.091~0.029	−1.229	244	0.22
	Visitor	43	0.69	0.18					
	Total	246	0.67	0.18					
F	Non-visitor	203	0.86	0.22	−0.05	−0.119~0.028	−1.229	244	0.22
	Visitor	43	0.91	0.23					
	Total	246	0.87	0.22					
I	Non-visitor	203	0.77	0.19	−0.12	−0.181~−0.056	−3.729	244	0.000 ***
	Visitor	43	0.88	0.19					
	Total	246	0.79	0.19					
Active Landscape Visual Quality Group	Non-visitor	203	0.78	0.15	−0.07	−0.119~−0.021	−2.826	244	0.005 **
	Visitor	43	0.85	0.15					
	Total	246	0.79	0.15					
D	Non-visitor	203	−0.41	0.12	−0.04	−0.077~0.001	−1.909	244	0.057
	Visitor	43	−0.37	0.13					
	Total	246	−0.4	0.12					
G	Non-visitor	203	−0.65	0.19	−0.08	−0.142~−0.011	−2.286	244	0.023 *
	Visitor	43	−0.57	0.24					
	Total	246	−0.63	0.2					
H	Non-visitor	203	−0.57	0.16	−0.1	−0.184~−0.020	−2.49	48.819	0.016 *
	Visitor	43	−0.47	0.26					
	Total	246	−0.55	0.18					
L	Non-visitor	203	−0.28	0.1	−0.07	−0.106~−0.036	−3.983	244	0.000 ***
	Visitor	43	−0.21	0.13					
	Total	246	−0.27	0.11					
Passive Landscape Visual Quality Group	Non-visitor	203	−0.48	0.11	−0.07	−0.127~−0.016	−2.603	48.742	0.012 *
	Visitor	43	−0.41	0.17					
	Total	246	−0.47	0.12					

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 7. Non-resident and resident variables: *t*-test results.

Group	Variable	N	Mean	Std.	Mean Value Difference	Difference 95% CI	*t*	*df*	*p*
A	Non-resident	215	0.83	0.21	−0.06	−0.138~0.015	−1.593	244	0.112
	Resident	31	0.89	0.16					
	Total	246	0.84	0.2					

Table 7. *Cont.*

Group	Variable	N	Mean	Std.	Mean Value Difference	Difference 95% CI	*t*	*df*	*p*
C	Non-resident	215	0.66	0.18	−0.08	−0.145~−0.010	−2.266	244	0.024 *
	Resident	31	0.74	0.18					
	Total	246	0.67	0.18					
F	Non-resident	215	0.87	0.22	−0.02	−0.101~0.068	−0.394	244	0.694
	Resident	31	0.88	0.25					
	Total	246	0.87	0.22					
I	Non-resident	215	0.77	0.19	−0.09	−0.162~−0.017	−2.433	244	0.016 *
	Resident	31	0.86	0.19					
	Total	246	0.79	0.19					
Active Landscape Visual Quality Group	Non-resident	215	0.78	0.15	−0.06	−0.118~−0.005	−2.151	244	0.032 *
	Resident	31	0.84	0.13					
	Total	246	0.79	0.15					
D	Non-resident	215	−0.4	0.12	−0.01	−0.056~0.034	−0.487	244	0.627
	Resident	31	−0.39	0.13					
	Total	246	−0.4	0.12					
G	Non-resident	215	−0.64	0.2	0	−0.079~0.073	−0.08	244	0.936
	Resident	31	−0.63	0.19					
	Total	246	−0.63	0.2					
H	Non-resident	215	−0.55	0.18	0.01 *	−0.060~0.078	0.249	244	0.804
	Resident	31	−0.56	0.21					
	Total	246	−0.55	0.18					
L	Non-resident	215	−0.27	0.11	0.01 *	−0.028~0.054	0.628	244	0.53
	Resident	31	−0.28	0.11					
	Total	246	−0.27	0.11					
Passive Landscape Visual Quality Group	Non-resident	215	−0.47	0.12	0	−0.045~0.048	0.082	244	0.935
	Resident	31	−0.47	0.12					
	Total	246	−0.47	0.12					

* $p < 0.05$.

Table 8. ANOVA test results for the active and passive visual quality group.

Group	Variable	N	Mean	Std.	*F*	*p*
A	18 to 25 years old	53	0.82	0.19	3.173	0.025 *
	26 to 35 years old	125	0.85	0.2		
	36 to 45 years old	37	0.89	0.21		
	Above 46 years old	31	0.75	0.19		
	Total	246	0.84	0.2		
C	18 to 25 years old	53	0.65	0.17	4.178	0.007 **
	26 to 35 years old	125	0.7	0.18		
	36 to 45 years old	37	0.68	0.18		
	Above 46 years old	31	0.57	0.18		
	Total	246	0.67	0.18		

Table 8. *Cont.*

Group	Variable	N	Mean	Std.	*F*	*p*
F	18 to 25 years old	53	0.87	0.2	3.173	0.025 *
	26 to 35 years old	125	0.9	0.21		
	36 to 45 years old	37	0.85	0.25		
	Above 46 years old	31	0.77	0.24		
	Total	246	0.87	0.22		
I	18 to 25 years old	53	0.76	0.2	2.301	0.078
	26 to 35 years old	125	0.81	0.2		
	36 to 45 years old	37	0.79	0.18		
	Above 46 years old	31	0.72	0.17		
	Total	246	0.79	0.19		
Active Landscape Visual Quality Group	18 to 25 years old	53	0.77	0.14	5.162	0.002 **
	26 to 35 years old	125	0.82	0.15		
	36 to 45 years old	37	0.8	0.15		
	Above 46 years old	31	0.7	0.14		
	Total	246	0.79	0.15		
D	18 to 25 years old	53	−0.42	0.12	3.448	0.017 *
	26 to 35 years old	125	−0.38	0.12		
	36 to 45 years old	37	−0.45	0.11		
	Above 46 years old	31	−0.41	0.11		
	Total	246	−0.4	0.12		
G	18 to 25 years old	53	−0.63	0.18	3.049	0.029 *
	26 to 35 years old	125	−0.6	0.22		
	36 to 45 years old	37	−0.69	0.18		
	Above 46 years old	31	−0.7	0.17		
	Total	246	−0.63	0.2		
H	18 to 25 years old	53	−0.54	0.16	1.278	0.283
	26 to 35 years old	125	−0.54	0.2		
	36 to 45 years old	37	−0.61	0.18		
	Above 46 years old	31	−0.56	0.17		
	Total	246	−0.55	0.18		
L	18 to 25 years old	53	−0.28	0.1	4.619	0.004 **
	26 to 35 years old	125	−0.25	0.11		
	36 to 45 years old	37	−0.31	0.1		
	Above 46 years old	31	−0.31	0.1		
	Total	246	−0.27	0.11		
Passive Landscape Visual Quality Group	18 to 25 years old	53	−0.47	0.11	3.809	0.011 *
	26 to 35 years old	125	−0.44	0.13		
	36 to 45 years old	37	−0.51	0.11		
	Above 46 years old	31	−0.5	0.11		
	Total	246	−0.47	0.12		

* $p < 0.05$, ** $p < 0.01$.

Table 9. The results of post hoc multiple comparison test of the active and passive visual quality groups.

Group	(I) Variable	(J) Variable	(I) Mean	(J) Mean	*Dif* (I–J)	*p*
A	1	2	0.819	0.851	−0.032	1
	1	3	0.819	0.886	−0.068	0.683
	1	4	0.819	0.748	0.07	0.71
	2	3	0.851	0.886	−0.035	1
	2	4	0.851	0.748	0.103	0.064
	3	4	0.886	0.748	0.138	0.028 *
C	1	2	0.649	0.696	−0.047	0.64
	1	3	0.649	0.676	−0.027	1
	1	4	0.649	0.574	0.075	0.374
	2	3	0.696	0.676	0.02	1
	2	4	0.696	0.574	0.122	0.004 **
	3	4	0.676	0.574	0.101	0.115
F	1	2	0.868	0.901	−0.033	1
	1	3	0.868	0.849	0.019	1
	1	4	0.868	0.768	0.1	0.269
	2	3	0.901	0.849	0.052	1
	2	4	0.901	0.768	0.133	0.017 *
	3	4	0.849	0.768	0.081	0.791
I	1	2	0.758	0.813	−0.054	0.516
	1	3	0.758	0.789	−0.031	1
	1	4	0.758	0.723	0.036	1
	2	3	0.813	0.789	0.024	1
	2	4	0.813	0.723	0.09	0.121
	3	4	0.789	0.723	0.067	0.935
Active Landscape Visual Quality Group	1	2	0.774	0.815	−0.042	0.502
	1	3	0.774	0.8	−0.026	1
	1	4	0.774	0.703	0.07	0.205
	2	3	0.815	0.8	0.015	1
	2	4	0.815	0.703	0.112	0.001 **
	3	4	0.8	0.703	0.097	0.042 *
D	1	2	−0.415	−0.382	−0.033	0.532
	1	3	−0.415	−0.449	0.034	1
	1	4	−0.415	−0.413	−0.002	1
	2	3	−0.382	−0.449	0.066	0.016 *
	2	4	−0.382	−0.413	0.031	1
	3	4	−0.449	−0.413	−0.036	1

Table 9. *Cont.*

Group	(I) Variable	(J) Variable	(I) Mean	(J) Mean	*Dif* (I–J)	*p*
G	1	2	−0.63	−0.605	−0.025	1
	1	3	−0.63	−0.686	0.056	1
	1	4	−0.63	−0.703	0.073	0.622
	2	3	−0.605	−0.686	0.082	0.169
	2	4	−0.605	−0.703	0.098	0.083
	3	4	−0.686	−0.703	0.017	1
H	1	2	−0.543	−0.541	−0.003	1
	1	3	−0.543	−0.605	0.062	0.679
	1	4	−0.543	−0.561	0.018	1
	2	3	−0.541	−0.605	0.065	0.355
	2	4	−0.541	−0.561	0.02	1
	3	4	−0.605	−0.561	−0.044	1
L	1	2	−0.279	−0.25	−0.03	0.548
	1	3	−0.279	−0.308	0.029	1
	1	4	−0.279	−0.31	0.03	1
	2	3	−0.25	−0.308	0.059	0.022 *
	2	4	−0.25	−0.31	0.06	0.032 *
	3	4	−0.308	−0.31	0.002	1
Passive Landscape Visual Quality Group	1	2	−0.467	−0.444	−0.023	1
	1	3	−0.467	−0.512	0.045	0.492
	1	4	−0.467	−0.497	0.03	1
	2	3	−0.444	−0.512	0.068	0.018 *
	2	4	−0.444	−0.497	0.052	0.19
	3	4	−0.512	−0.497	−0.015	1

Variables (I–J) 1, 2, 3, and 4, respectively, represent the following groups: 18 to 25 years old, 26 to 35 years old, 36 to 45 years old, and over 46 years old. * $p < 0.05$, ** $p < 0.01$.

From the perspective of the passive picture group, picture group D shows significance at the 0.05 level (F = 3.448, p = 0.017), and an obvious difference is reflected in "Age group 2 > Age group 3". Picture group G shows significance at the 0.05 level (F =3.049, p = 0.029), and a significant difference is reflected in "Age 2 Group > Age 4 Group"; and picture group L shows a significance level of 0.01 (F = 4.619, p = 0.004), with a significant difference reflected in "Age group 2 > Age group 3; Age group 2 > Age group 4".

From the above data analysis, it can be seen that among the four age groups, age groups 2 and 3 have the strongest characteristics, and age group 4 is more significant than age group 1. In the active picture group, the C, F, and ACT picture groups show obvious characteristics, with age group 2 being more significant than age group 4. In the passive picture group, the D, L, and PAS picture groups show obvious characteristics, with age being group 2 more significant than age group 3. It can be seen that perception among age group 3 is stronger than among age groups 4 and 1 for the passive picture group (Figure 4a–d), and overall, subjects in age groups 2 and 3 are more likely to be attracted to landscape features. In both the active and passive picture groups, age group 2 is stable in terms of perception, while age groups 3 and 4 show significant differences (Figure 4e–h). In the active picture group, age group 4 is considerably more significant than age group 3, while in the passive picture group, age group 3 is considerably more significant than age group 4.

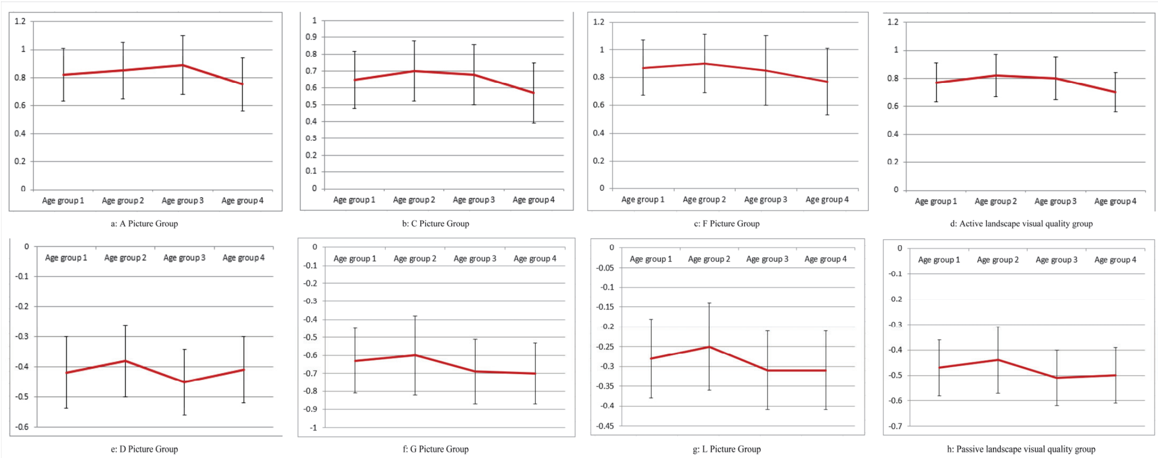

Figure 4. Analysis of visual perception bias of participants in different age groups towards different photo groups.

4. Discussion

4.1. The Impact of Landscape Elements on the Visual Quality of Rural Landscapes

This study demonstrates that landscape elements play an important role in influencing the public perception of visual quality. Specifically, the active visual quality identified by the public, primarily characterized by fields, transforms into passive visual quality, primarily characterized by mixed vegetation or artificial structures. In the active landscape visual quality group, field landscape elements are important influencing factors of visual quality. Fields represent a specific form of agricultural landscape; they not only provide economic value, but also provide various ecosystem services (ESs) to society, as well as other substantial benefits [54]. Secondly, cultural ecosystem services that provide recreational, esthetic, and spiritual benefits can also be established in relation to these landscape elements [55].

In the passive landscape visual quality group, vegetation and landscape elements are the dominant elements of the landscape scene; they are not popular in the rural landscape of the study area and provide an unpleasant visual experience [44]. However, the reason vegetation was perceived to impart passive visual quality in this study was due to low vegetation density and its disordered distribution in the near field. At the same time, there are few types of human-made landscape elements, and their distribution is scattered. They lack unity in form and color as well as regional characteristics. The dominance of human-made landscape elements in the spatial scene detracts from the quality of the space and directly affects the viewer's senses, which, in turn, leads to feelings of disgust and reduces their preference for such landscapes.

Compared to human-made landscapes, natural landscapes generated a higher consensus among respondents, possibly because humans have lived in natural environments for most of their evolutionary history. The human perception of the natural environment is very similar. On the other hand, human-made landscapes are easily influenced by culture; individuals from different cultural groups have different perceptions of human-made landscapes, thus leading to considerable differences in esthetic judgments [56].

4.2. The Impact of Visual Characteristics on the Visual Quality of Rural Landscapes

This study utilized nine key visual characteristics based on the landscape perception theory proposed by Tevit and selected some of these key characteristics to analyze the visual quality of rural landscapes.

In the active visual quality group, the landscape elements presented in the spatial scene have orderly characteristics, creating a comfortable visual experience for the public. From the perspective of spatial composition and landscape element composition, the spatial composition is balanced and the landscape elements in the space form a rhythmic repetition and are clear and organized, achieving visual coherence, unity, and complexity. Landscapes with visual images perceived in this way are preferred over those that appear disorderly [57]. At the same time, existing research shows that individual preferences are directly related to the openness of the space. Respondents prefer landscape scenes with high openness and a high sense of order [58].

However, in the passive visual quality group, the spatial scene presents diverse, intricately intertwined, and disorderly landscape elements, such as a disorganized combination of vegetation and human-made landscape elements, forming a relatively low degree of visual openness and thereby causing the public to have a passive visual experience. The visual openness of the five passive visual quality groups is worse than that of the active visual quality group. The public preference for such landscapes is also reduced due to their generally lower level of openness. At the same time, this diversity, complexity, and disorder in landscape elements conform with the complexity of visual characteristics [21]. However, Kaplan and other scholars conducted further analyses and research and divided complexity into ordered and disordered categories [27]. Ordered complexity creates visually rich variety in a scene, while disordered complexity is perceived as chaos [59]. Therefore, the visual quality of landscapes dominated by a single type of vegetation or patches of vegetation is better than other landscapes in the passive visual quality group (LC-11). Interference with the visual features of the landscape is another contributing element to passive visual quality. Interference is usually represented by elements in the landscape that lack contextual suitability and coherence [60]. In the passive visual quality group, major interference factors come from the overall spatial environment being uncoordinated, are abrupt, and indirectly become visual pollutants in artificial landscape elements, such as vegetation, single objects, construction, etc. Therefore, on the one hand, the existence of these elements will distract the public's visual focus, and on the other hand, it will disrupt the coherence of the spatial continuity narrative, thereby producing an unpleasant visual experience.

4.3. The Impact of Subjects' Demographic Characteristics on Preferences

This study shows that, to a certain extent, there are differences in preferences for landscape characteristics due to the influence of the demographics of the population, such as whether they are residents, whether they have visited the study area before, and the age of the subjects; these influencing factors are reflected in both the active and passive visual quality groups. Specifically, residents of the southwest Guizhou region and those who have visited this area can be regarded as familiar with the environment. Existing research results show that familiarity is important in visual landscape evaluation, primarily relating to the existing place and the participant's current place of residence [61]. The relationship between people and places has been identified by relevant research as an important factor affecting visual landscape preference [62], among which familiarity with landscape types is a key element [63]. Regarding age, existing studies have found that landscape preference changes with age [64,65], and this conclusion was verified in this study. The difference is that existing research shows that preference differences affecting landscape characteristics mainly manifest between generations, such as between children and older people [66]. In the current research results, the analyzed preference differences have a certain degree of consistency with existing research results, but new situations have also emerged, such as different age groups having opposite feelings about the same types of landscape features. However, there is a lack of evidence to verify the reasons for the differences between the two age groups in terms of active versus passive picture quality.

5. Conclusions

This study uses a public preference survey combined with an eye movement heat map method to evaluate the visual quality of rural landscapes in southwestern Guizhou, China. This study shows that in the current reality of rapid urban and rural development, protecting the unique features of rural areas is of great value and significance. Research shows that topography, landforms, and field landscape elements play an important role in the rural landscape characteristics of southwestern Guizhou, China, contributing significantly to improving the overall visual quality of the region. Although the public shows an aversion to vegetation in terms of visual quality, vegetation elements play an irreplaceable role in rural landscapes. There are two reasons for this aversion to vegetation. On the one hand, participants dislike disordered vegetation and a lack of proper planning. On the other hand, cultural elements in rural landscapes have a significant passive impact on the visual experience of the landscape. It is crucial to reasonably and skillfully integrate artificial landscape elements into rural environments to supplement and improve these environments instead of damaging them.

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Appendix A

Table A1. The six pictures with the highest scores in the active group and the six pictures with the lowest scores in the passive group.

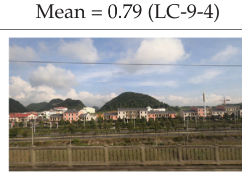
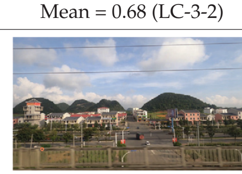
	Photos	
Active Landscape Visual Quality		
	Mean = 0.87 (LC-6-3)	Mean = 0.83 (LC-1-2)
		
	Mean = 0.79 (LC-9-4)	Mean = 0.68 (LC-3-2)
		
	Mean = 0.66 (LC-3-3)	Mean = 0.64 (LC-3-5)

Table A1. *Cont.*

	Photos	
Passive Landscape Visual Quality		
	Mean = −0.64 (LC-7-2)	Mean = −0.57 (LC-8-4)
		
	Mean = −0.48 (LC-4-3)	Mean = −0.39 (LC-4-4)
		
	Mean = −0.33 (LC-4-5)	Mean = −0.28 (LC-12-2)

Table A2. Pictures in each group sorted by mean score.

Group		Landscape Character	Code	Individual Mean Value	Average Value
Active Landscape Visual Quality	6	Field and landform landscape	LC-6-1	0.57	0.606
			LC-6-2	0.61	
			LC-6-3	0.87	
			LC-6-4	0.45	
			LC-6-5	0.53	
	1	Field landscape surrounded by mountains	LC-1-1	0.18	0.514
			LC-1-2	0.83	
			LC-1-3	0.673	
			LC-1-4	0.42	
			LC-1-5	0.51	
	9	Plateau landform natural landscape	LC-9-1	0.36	0.486
			LC-9-2	0.25	
			LC-9-3	0.48	
			LC-9-4	0.79	
			LC-9-5	0.55	
	3	Plateau landforms and roadside strip settlement buildings	LC-3-1	0.22	0.438
			LC-3-2	0.68	
			LC-3-3	0.66	
			LC-3-4	−0.01	
			LC-3-5	0.64	

Table A2. *Cont.*

Group		Landscape Character	Code	Individual Mean Value	Average Value
	2	Natural landforms, fields, and settlement landscapes	LC-2-1	0.18	0.26
			LC-2-2	0.24	
			LC-2-3	0.33	
			LC-2-4	0.15	
			LC-2-5	0.38	
	5	Settlement and landscape	LC-5-1	0.08	0.086
			LC-5-2	0.12	
			LC-5-3	−0.01	
			LC-5-4	−0.02	
			LC-5-5	0.26	
Moderate Visual Quality (M = 0)					
Passive Landscape Visual Quality	7	Plateau landform settlements and winding rural roads	LC-7-1	−0.26	−0.272
			LC-7-2	−0.64	
			LC-7-3	−0.18	
			LC-7-4	−0.03	
			LC-7-5	−0.25	
	8	Viaduct connecting mountains	LC-8-1	−0.21	−0.244
			LC-8-2	−0.15	
			LC-8-3	−0.11	
			LC-8-4	−0.57	
			LC-8-5	−0.18	
	4	Plateau landforms and scattered settlement buildings	LC-4-1	−0.05	−0.242
			LC-4-2	0.04	
			LC-4-3	−0.48	
			LC-4-4	−0.39	
			LC-4-5	−0.33	
	12	Field landscape	LC-12-1	−0.11	−0.15
			LC-12-2	−0.28	
			LC-12-3	−0.18	
			LC-12-4	−0.06	
			LC-12-5	−0.12	
	10	Field and settlement landscape	LC-10-1	0.01	−0.05
			LC-10-2	−0.08	
			LC-10-3	−0.02	
			LC-10-4	−0.05	
			LC-10-5	−0.11	
	11	Settlement and plant landscape	LC-11-1	−0.01	−0.028
			LC-11-2	−0.04	
			LC-11-3	−0.02	
			LC-11-4	−0.03	
			LC-11-5	−0.04	

Figure A1. Groups of landscape characters. Note: n-1, n-2, n-3, n-4, n-5 (n = 1, 2, 3,. . .,12) represent different sampled images of the same landscape type.

Table A3. Heat map analysis to identify key features and elements of visual quality.

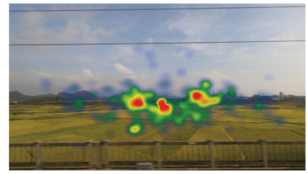
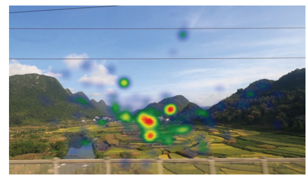
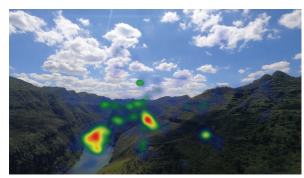
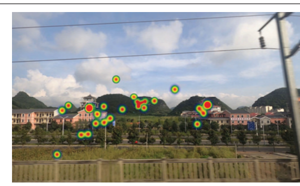
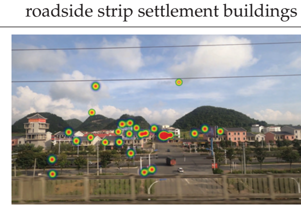
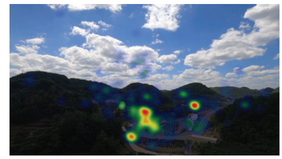
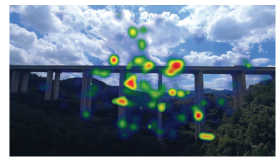
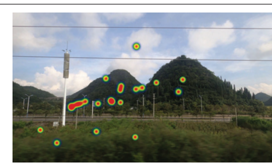
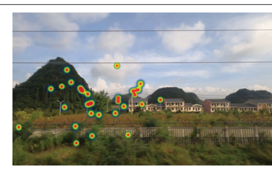
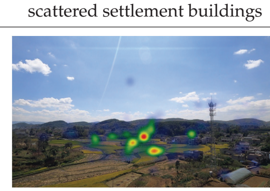
	Photos Collected	Eye Tracking Analysis (Heat Map)
Active Landscape Visual Quality		
	1. Group (Mean), Landscape Character	6 (LC-6-3, Mean = 0.87), Fields and natural landscapes
		
	2. Group (Mean), Landscape Character	1 (LC-1-2, Mean = 0.83), Field landscape surrounded by mountains
		
	3. Group (Mean), Landscape Character	9 (LC-9-4, Mean = 0.79), Plateau landform natural landscape
		
	4. Group (Mean), Landscape Character	3 (LC-3-2, Mean = 0.68), Plateau landforms and roadside strip settlement buildings
		
	5. Group (Mean), Landscape Character	3 (LC-3-3, Mean = 0.66), Plateau landforms and roadside strip settlement buildings
		
	6. Group (Mean), Landscape Character	3 (LC-3-5, Mean = 0.64), Plateau landforms and roadside strip settlement buildings

Table A3. *Cont.*

	Photos Collected	Eye Tracking Analysis (Heat Map)
	Moderate Visual Quality (M = 0)	
Passive Landscape Visual Quality		
	1. Group (Mean), Landscape Character	7 (LC-7-2, Mean = −0.64), Plateau landform settlements and winding rural roads
		
	2. Group (Mean), Landscape Character	8 (LC-8-4, Mean = −0.57), Viaduct connecting mountains
		
	3. Group (Mean), Landscape Character	4 (LC-4-3, Mean = −0.48), Plateau landforms and scattered settlement buildings
		
	4. Group (Mean), Landscape Character	4 (LC-4-4, Mean = −0.39), Plateau landforms and scattered settlement buildings
		
	5. Group (Mean), Landscape Character	4 (LC-4-5, Mean = −0.33), Plateau landforms and scattered settlement buildings
		
	6. Group (Mean), Landscape Character	12 (LC-12-2, Mean = −0.28), Field landscape

Note: Eye Tracking Analysis (Heat map) is a record that characterizes the visual behavior of participants when viewing images.

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Article

The Influence of Perceived Physical and Aesthetic Quality of Rural Settlements on Tourists' Preferences—A Case Study of Zhaoxing Dong Village

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Abstract: Rural settlements, as crucial human habitats, encompass various values such as residential living, cultural tourism, and industrial development. This paper investigates the environmental physical and aesthetic factors perceived by tourists, which influence their preferences for rural settlement environments. Previous studies have predominantly focused on evaluating the impacts of physical or aesthetic factors on tourists' environmental preferences, with limited research simultaneously examining their combined effects. To reduce this research gap, we selected Zhaoxing Dong Village in China, characterized by typical rural environmental traits, and collected 450 valid questionnaires. The questionnaire data underwent correlation analysis and multiple linear regression analysis. The results indicate that when considering only environmental physical quality factors, most of the physical quality factors are significantly correlated with tourists' preferences. Among them, "visual quality" shows the highest correlation, followed by "facility" and "maintenance", while "security" shows the lowest correlation. When aesthetic quality factors are added to the model as independent variables, they enhance the explanatory power of the model and exhibit more significant associations compared to the relationship between physical quality factors and preferences. Among the aesthetic quality factors, "multisensory" and "sublime" demonstrate the highest correlation, whereas "diversity" shows the lowest correlation. The current study demonstrates the validity of the two scales for measuring tourists' perceived levels of physical and aesthetic quality in rural settlement environments. These findings contribute to the effective utilization of environmental capital within rural settlements and provide guidance for rural settlement planning and design.

Keywords: environmental quality; Zhaoxing Dong Village; perception measurement; rural settlements; environmental preferences

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1. Introduction

Rural settlements are important places for human living and activities [1]. They are shaped by diverse factors such as the geographical environment, socio-economic conditions, and historical and cultural heritage, resulting in distinct settlement patterns and local traditions [2–4]. Comprising various cultural ecosystem services and practical functions, rural settlements not only provide habitats for local communities but also create significant value in terms of agricultural production [5,6], cultural heritage preservation and inheritance [7,8], cultural landscape creation [9], as well as leisure and tourism [10–12]. As a vast multi-ethnic country, China possesses abundant local and ethnic cultures, giving rise to diverse rural settlements characterized by unique geographical environments and historical backgrounds. However, in the era of globalization, rapid urbanization in China has irreversibly damaged the fragile ecological fabric of rural settlements [13]. Many rural settlements are confronted with issues such as "constructive destruction", the hollowing out of villages, and cultural disconnection [14]. Despite the implementation of the "Regulations on the Protection of Historical and Cultural Cities, Towns, and Villages" (https://www.gov.cn/zhengce/2020-12/27/content_5574469.htm, accessed on 8 June 2023) by the Chinese government in 2008, the increasing urbanization and modernization have resulted in a noticeable "gap" between the infrastructure conditions of rural settlements and the growing demand for high-quality spatial resources.

The environment of rural settlements has a profound impact on the well-being of the population [15]. High-quality rural settlement environments not only play a crucial role in cultural dissemination and promoting local economic development [16], but also offer numerous benefits to the users and visitors. For instance, the aesthetic value of rural environments can alleviate the impact of stress-inducing life events on mental health [17,18], and they can also attract tourism [19] and leisure activities while enhancing the life satisfaction of local residents [20]. Several studies have simultaneously demonstrated the positive impacts of high-quality spatial elements in rural settlements on tourists, which are closely related to cultural, ecological, and aesthetic values. In summary, the quality of rural settlement environments plays a significant and multifaceted role. Investigating and researching the quality of rural settlement environments is of great importance, as these studies can uncover the relationship between these qualities and their benefits, thus providing insights for environmental planning and management to bridge the gap between development and conservation. However, despite the increasing attention being paid to rural settlements as cultural and tourism destinations, attracting more tourists through improving environmental quality remains a challenge [21]. There may be a correlation between tourists' environmental preferences and the enhancement of rural environments. From the perspective of tourists, the elements of travel, accommodation, food, leisure, shopping, and entertainment in rural settlements exhibit different emotions, perceptions, and psychological tendencies during the tourism process [22]. Exploring these psychological inclinations can provide a more focused reflection on actual environmental improvement issues. In addition, high-quality environments generate greater interest among tourists, attracting more tourism activities. For instance, the aesthetic quality, historical and cultural significance, and comfortable experiences of the environment influence tourists' preferences and their choices regarding the sequence of visiting attractions. In the study of Sojasi Qidari et al. (2016), it is also proved that there is a relationship between environmental quality and tourism attractiveness, and that the improvement of physical quality and aesthetic quality plays a positive role in improving the attractiveness of rural tourism and will affect users' tourism choices [23]. Therefore, studying the influence of environmental quality on tourists' preference is very important to the improvement of rural settlement environment, tourism attractiveness, service management and planning decision-making [24].

The study of environmental preferences can be traced back to the 1960s and is often defined as the "liking" or search for aesthetically pleasing locations [25,26]. Environmental preferences are determined by the environmental features that have potential functional significance to the perceiver [27]. Due to the interactions, perceptions, and information biases between individuals and the environment, users may have different aesthetic preferences for the environment [28]. Also, the environmental preferences may be influenced by factors such as age, culture, level of education, and residential environment [29].

Although there are many factors that influence user environmental preferences, the relationship between environmental quality and preferences has been widely emphasized [30,31]. The physical environment plays an important role in shaping tourist preferences, such as topographical changes [32], vegetation greening [33], visual aspects of the environment [34], and the quantity of elements [35]. Topographical changes can enrich the comfort and enjoyment of tourists. Altering the position and shape of paths among forests can provide unique walking experiences for tourists [36]. Increasing or decreasing the height and steepness of hills can enhance the pleasure and sense of challenge during climbing [37]. Abundant vegetation greening can provide a more oxygenated environment, promote physical activity, and evoke positive emotions [38]. Moreover, facilities and management [38], as well as artificial elements [39], also play a significant role in tourists' environmental preferences. On the other hand, the aesthetic quality of the environment may influence tourist preferences, as it is a form of aesthetic experience [40]. Typically, studies on physical environmental quality evaluate the physical characteristics or attributes of the environment, while studies on aesthetic quality assess the cognitive and aesthetic responses of tourists after their multisensory interactions with the environment [41]. Previous research on environmental aesthetics has primarily focused on the visual aspects, such as visual coherence [42], visual focus [33], and visual complexity [43]. Although these visual experiences are crucial, they neglect the impact of multisensory experiences on preferences, such as the influence of visual and auditory stimuli [44], the effect of tactile and olfactory sensations on preferences [45], and the sense of mystery that encourages further exploration [46]. However, previous studies on the relationship between environmental quality and preferences have often discussed physical features or aesthetic perceptions in isolation, rarely considering both aspects of environmental quality simultaneously. Human evaluations of the environment are not isolated psychological processes but rather results based on the joint action of the physical environment and related emotional and cognitive structures [47]. For example, tourists can perceive the artificial facilities conditions (physical quality factors) and the diversity of scenery (aesthetic quality factors) at the same time, meaning that they can make a more comprehensive and accurate evaluation of the environment of the scenic area [48]. Therefore, it is essential to consider both physical quality and aesthetic quality comprehensively when discussing environmental preferences.

In conclusion, environmental quality comprises both physical quality and aesthetic quality, both of which jointly influence individuals' perception and evaluation of the environment. Previous research on environmental quality has mostly focused on urban streets [49], building interior [50], blue–green space [51] and other areas, with less emphasis on the study of rural settlement environments. The purpose of this study is to establish the link between tourist preferences and environmental quality by investigating tourists' perceptions of the environmental quality of rural settlements. It aims to gain a comprehensive understanding of tourists' environmental preferences to support environmental improvement, service management, and planning decisions for rural settlements. The specific objectives are as follows:

(1) Measure tourists' evaluations of the physical quality of the rural settlement environment.
(2) Measure tourists' evaluations of the aesthetic quality of the rural settlement environment.
(3) Establish the relationship between tourists' environmental preferences and these two aspects of environmental quality.

2. Method

2.1. Study Sites

This study was conducted in Zhaoxing Dong Village, located in Liping County, Qiandongnan Miao-Dong Autonomous Prefecture, Guizhou Province, southwestern China (Figure 1). The village is approximately 72 km away from Liping County, covering an area of about 180,000 square meters [52], and is home to over 1100 households and more than 6000 residents. It is one of the largest Dong ethnic villages in China [53]. Geographically, the village is situated in a basin surrounded by mountains, with a river formed by the convergence of two small streams flowing through the village. The architectural layout of the village follows the river and topography, forming a linear pattern. The village is characterized by wooden stilted structures constructed from Chinese fir, consisting of residential buildings and public buildings. The latter includes drum towers, covered bridges, opera stages, village gates, etc., serving as visual focal points of the architectural landscape and central spaces for public activities. The village is surrounded by farmland and forests, visually harmonizing with the natural environment, providing a foundation for local agricultural and forestry development. As a historically and culturally renowned village in China, Zhaoxing Dong Village is one of the earliest developed Dong ethnic villages. It has a rich historical heritage and cultural landscape, attracting a large number of tourists for sightseeing and cultural experiences. According to statistics, Zhaoxing Dong Village received more than 1.6 million tourists in 2022, generating substantial tourism revenue for the local community and possessing significant value in terms of environmental protection and tourism development [54].

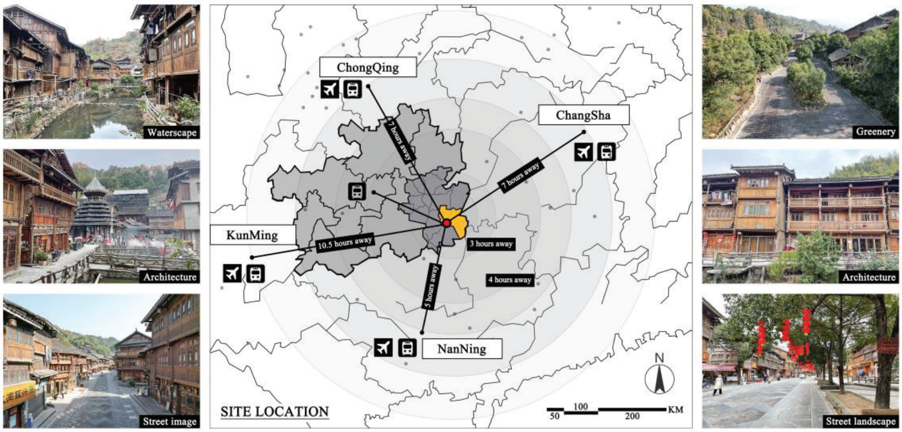

Figure 1. The location and photos of the study site (by author).

However, with the development of urbanization and the tourism industry, many rural buildings and landscapes are being transformed or renovated. These construction activities are primarily based on the preferences of planners or economic considerations [55], often neglecting the preferences of residents or tourists. As a result, the outcomes of these designs may not always align with the needs of the users. Therefore, this study evaluates a variety of environmental qualities in this rural settlement space and analyzes their impact on tourists' evaluation of this environmental setting (that is, the extent to which the environment is liked, representing the individual's preference for this environment). This research aims to provide a basis for the targeted improvement of environmental quality, in order to protect the village environment, attract more tourist activities, and promote local economic growth.

2.2. The Questionnaire

In order to assess the physical quality of the rural settlement environment, we referred to the relevant literature on physical environmental quality studies [48,56,57]. These studies have demonstrated that physical factors (or physical features) significantly influence the relationship between tourists and the environment, such as safety and security, infrastructure conditions, visual quality of the site, and management and maintenance. We adapted some of these items to better match our research focus on rural settlement environments.

The initial version of the questionnaire was evaluated by an expert panel organized by the first author, which included 5 PhD holders and 10 graduate students. Some items that were deemed difficult to answer were removed, such as "visibility of the scenery" and "visual pollution" in the evaluation of physical environmental quality, as well as statements related to aesthetic quality such as "well-maintained." These panel members were experts in landscape design, environmental science, ecology, and urban planning from the author's institution. The final version of the questionnaire consisted of 20 items divided into four sections and used a 7-point Likert scale for rating descriptions [57]. In this scale, 1 represented a low perception level (very poor/very few), and 7 represented a high perception level (very good/very high) (Table 1).

Table 1. Questionnaire for physical environment quality evaluation.

Category	Statement	Score
SE (Security)	(1) How is the public security environment of the village? (The higher the score, the safer you feel.)	Very poor 1–7 Very good
	(2) How is the security infrastructure of the village? (e.g., guardrails, handrails)	Very poor 1–7 Very good
	(3) Are the lighting facilities in the village sufficient?	Very poor 1–7 Very good
FA (Facility)	(4) How are the dining service conditions in the village?	Very poor 1–7 Very good
	(5) How are the commercial services such as retail and shopping in the village?	Very poor 1–7 Very good
	(6) How are the accommodation conditions in the village?	Very poor 1–7 Very good
	(7) How are the road and traffic conditions in the village?	Very poor 1–7 Very good
	(8) How are the conditions of traffic guidance facilities? (e.g., road signs, guide map)	Very poor 1–7 Very good
VI (Visual quality)	(9) How is the overall visual aesthetics of the site?	Very poor 1–7 Very good
	(10) How is the visual appearance of pedestrian paths in the site?	Very poor 1–7 Very good
	(11) How is the visual appearance of residential buildings in the site?	Very poor 1–7 Very good
	(12) How is the visual aesthetics of public buildings in the site?	Very poor 1–7 Very good
	(13) How is the visual attractiveness of natural landscapes in the site?	Very poor 1–7 Very good
	(14) How is the attractiveness of vegetation in the site?	Very poor 1–7 Very good
MA (Maintenance)	(15) How is the maintenance and management of sidewalks in the village?	Very poor 1–7 Very good
	(16) How is the maintenance of hard surfaces in the village? (e.g., squares, roads)	Very poor 1–7 Very good
	(17) How is the maintenance of buildings in the village?	Very poor 1–7 Very good
	(18) How is the vegetation management in the village?	Very poor 1–7 Very good
	(19) How is the maintenance of street facilities in the village? (e.g., street lamps, trash cans, road signs)	Very poor 1–7 Very good
	(20) How is the maintenance of safety equipment such as guardrails in the village?	Very poor 1–7 Very good

For aesthetic quality, we referred to the research conducted by Subiza-Pérez et al. (2019) [58], who proposed a self-report tool based on factor analysis to assess the perceived aesthetic quality of spaces. This tool consisted of 23 statements divided into five components and demonstrated good internal consistency, thus proving its usefulness in urban planning research. Additionally, we consulted the study by Sevenant et al. (2009) [59] to expand the perception evaluation items that align with our project site. In this study, we applied the aforementioned tool and evaluation items to the research on rural settlement environments, while also referencing the work of Luo et al. (2023) [60] to ensure the accuracy of our item descriptions. Following expert evaluation and preliminary surveys, we removed items that were deemed difficult to answer or redundant, resulting in a simplified version comprising 31 items from eight components, which were evaluated on a 7-point Likert scale ranging from 1 (strongly disagree) to 7 (strongly agree) (Table 2).

In addition, this study used three questions to measure visitors' overall environmental preferences for the rural settlement environment (Zhaoxing Dong Village), including "How much do you like this place?", "Would you consider visiting again?", and "Would you recommend this place to a friend?" (1 = strongly dislike/strongly disagree, 7 = strongly like/strongly agree). The preference score for each visitor was the average of these three items. The final section of the questionnaire included basic background information about the respondents, such as gender, age, place of residence, income, and education level.

Table 2. Questionnaire for the evaluation of environmental aesthetic quality.

Category	Statement	Score
MU (Multisensory)	(1) The scenery here is beautiful.	Strongly disagree 1–7 Strongly agree
	(2) The sounds here are pleasant.	Strongly disagree 1–7 Strongly agree
	(3) The surface underfoot is comfortable.	Strongly disagree 1–7 Strongly agree
	(4) The air here is fresh or has a pleasant smell.	Strongly disagree 1–7 Strongly agree

Table 2. *Cont.*

Category	Statement	Score
DI (Diversity)	(5) The landscape here is diverse. (6) The vegetation here is diverse. (7) The architecture here is diverse. (8) The scenery here does not feel monotonous.	Strongly disagree 1–7 Strongly agree Strongly disagree 1–7 Strongly agree Strongly disagree 1–7 Strongly agree Strongly disagree 1–7 Strongly agree
UN (Unspoiled)	(9) The traditional architectural style here is well protected. (10) The natural environment here has not been damaged. (11) The traditional cultural atmosphere here is strong.	Strongly disagree 1–7 Strongly agree Strongly disagree 1–7 Strongly agree Strongly disagree 1–7 Strongly agree
PR (Protective)	(12) The architecture here is worth protecting. (13) The natural landscape here is worth protecting. (14) The folk culture here is worth protecting. (15) The folk art here is worth protecting.	Strongly disagree 1–7 Strongly agree Strongly disagree 1–7 Strongly agree Strongly disagree 1–7 Strongly agree Strongly disagree 1–7 Strongly agree
HI (Historical)	(16) The environment here makes me feel like it has a long history. (17) The architecture here makes me feel like it has a long history. (18) The folk festivals here make me feel like it has a long history. (19) The folk art here makes me feel like it has a long history.	Strongly disagree 1–7 Strongly agree Strongly disagree 1–7 Strongly agree Strongly disagree 1–7 Strongly agree Strongly disagree 1–7 Strongly agree
HA (Harmonious)	(20) Everything here matches the environment. (21) This place is easy to understand. (22) The scale of this place makes me happy and satisfied. (23) The different things and areas here form a coherent whole. (24) Staying here makes me feel comfortable inside.	Strongly disagree 1–7 Strongly agree Strongly disagree 1–7 Strongly agree Strongly disagree 1–7 Strongly agree Strongly disagree 1–7 Strongly agree Strongly disagree 1–7 Strongly agree
FA (Familiarity)	(25) This place seems familiar to me. (26) It can evoke memories I have had before. (27) I feel like I belong to this place, and it gives me a sense of belonging.	Strongly disagree 1–7 Strongly agree Strongly disagree 1–7 Strongly agree Strongly disagree 1–7 Strongly agree
SU (Sublime)	(28) This place is unique. (29) This place is very magnificent. (30) Staying here makes me feel small. (31) The beauty of this place makes me feel admiration and awe.	Strongly disagree 1–7 Strongly agree Strongly disagree 1–7 Strongly agree Strongly disagree 1–7 Strongly agree Strongly disagree 1–7 Strongly agree

2.3. Data Collection

Prior to conducting the main study, a preliminary questionnaire survey was conducted in the village, which was not included in the final sample. The preliminary survey aimed to test measures, wording, response formats, and implementation procedures, and to make modifications based on participants' feedback regarding any difficulties or issues encountered while answering the questionnaire. Additionally, a field investigation was conducted prior to the formal survey to identify specific locations with a high volume of visitors for on-site questionnaire distribution.

This study employed a sampling method to collect questionnaires, which is a non-probability sampling technique widely used in social science research and has demonstrated reliability [61,62]. The questionnaires were collected from 8 December 2022 to 5 January 2023 within Zhaoxing Dong Village between 9:00 AM and 5:00 PM. The first author approached visitors randomly at the survey site and provided them with the survey questionnaire, encouraging their companions to participate as well (Figure 2). All participants were informed about the research purpose and the anonymity of the survey to ensure questionnaire quality, and verbal consent was obtained from each participant. Field surveys were conducted only in comfortable weather conditions (no rain or strong winds) to control potential weather-related influences on the results.

Participation was voluntary. Some potential interviewees declined when approached, citing a lack of time, lack of knowledge, unwillingness to participate, and not wanting to be disturbed.

Figure 2. Photographs of the survey conducted by the first author in the study site (taken by author).

2.4. Statistical Analysis

SPSS version 27 (IBM, Armonk, NY, USA) was used for all statistical analyses in this study. Firstly, we examined the correlations between variables using Spearman's correlation coefficient. Secondly, we assessed the issue of multicollinearity in the questionnaire data. All predictor variables were within acceptable tolerance levels (>0.30) and VIF ratios (<4.00), indicating the absence of multicollinearity in the data for this study [63]. Finally, we conducted hierarchical linear regression analyses. In this study, overall environmental preference served as the dependent variable, while physical environmental quality and aesthetic quality were the independent variables. We constructed three regression models to examine the differences between demographic variables, physical environmental variables, aesthetic quality variables, and the overall model. In each model, demographic data were entered as control variables, physical environmental quality factors were entered in Model 2, and additional environmental aesthetic quality factors were included in Step 3. The significance level was set at $p < 0.05$.

3. Results

3.1. The Samples

Specific information on the sample of all respondents is shown in Table 3. A total of 458 questionnaires were collected in this survey, with 8 incomplete or invalid questionnaires, resulting in a response rate of 98.25%. The final sample consisted of 450 responses. Among them, there were 166 males, accounting for 36.9% of the total respondents, and 284 females, accounting for 63.1% of the total respondents. The majority of respondents were young adults aged 18–35 (n = 331, 73.6%), followed by the 35–55 age group (n = 107, 23.8%), and only 12 individuals (2.7%) were aged 55 and above. Most of the respondents were from urban areas (n = 323, 71.8%), while a small portion were from rural areas (n = 127, 28.2%). In terms of income, the majority of respondents had a monthly income ranging from CNY 4500 to 8000 (n = 172, 38.2%) or above CNY 8000 (n = 139, 30.9%), while a smaller proportion had a monthly income between CNY 2000 and 4500 (n = 74, 16.4%) or below CNY 2000 (n = 65, 14.4%). The educational background of the respondents was predominantly at the undergraduate level (n = 327, 72.7%).

3.2. Overall Statistics

The perception data are presented in Figure 3. Overall, in terms of physical environmental quality, the security dimension received the highest rating, with a mean score of 5.64 (±0.9), followed by the visual quality factor, with a score of 5.54 (±0.91), and the facility factor, with a score of 5.47 (±0.96), which suggests that visitors feel safer here and are more satisfied with the quality of the landscape and the facilities. The lowest rating was given to the maintenance, with a mean score of 5.32 (±0.97), indicating that it is necessary to strengthen the maintenance of the local landscape, buildings, and facilities. Regarding aesthetic quality, the highest rating was given to the protective dimension, with a mean score of 6.19 (±0.88), followed by a sense of history and multisensory beauty, with mean scores of 5.95 (±0.92) and 5.72 (±0.92), respectively, which means that protecting the local natural environment and cultural heritage and maintaining the historical atmosphere of the village as well as the multisensory beauty are important for the experience and preferences of tourists. The dimensions of harmonious, unspoiled, diversity, and sublime received moderate ratings, with mean scores of 5.71 (±0.88), 5.66 (±0.94), 5.31 (±1.07), and 5.07 (±1.11), respectively. The familiarity factor received the lowest rating, 4.97 (±1.32); this may be due to the fact that most tourists live in urban settings and have less experience of the rural settlement environment. Additionally, we validated the reliability of all components, with Cronbach's alpha ranging from 0.735 to 0.913, indicating high internal consistency.

Table 3. Socio-demographic characteristics of the sample.

	Category	Frequency	Percentage (%)
Gender	Male	166	36.9
	Female	284	63.1
Age	18–35	331	73.6
	35–55	107	23.8
	>55	12	2.7
Residential	Rural	127	28.2
	Urban	323	71.8
Income (Monthly, RMB)	<2000	65	14.4
	2000–4500	74	16.4
	4500–8000	172	38.2
	>8000	139	30.9
Education	Primary	8	1.8
	Junior	30	6.7
	Senior	44	9.8
	University	327	72.7
	Graduate	41	9.1

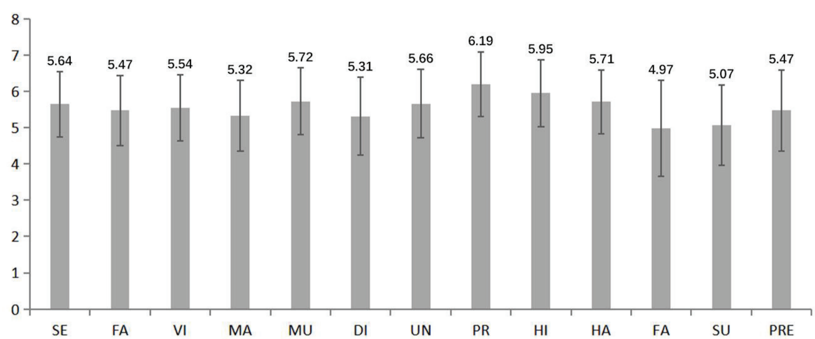

Figure 3. Overall statistics of the survey site (SE = Security. FA = Facility. VI = Visual quality. MA = Maintenance. MU = Multisensory. DI = Diversity. UN = Unspoiled. PR = Protective. HI = Historical. HA = Harmonious. FA = Familiarity. SU = Sublime. PRE = Preference).

3.3. Correlation Analysis

Table 4 summarizes correlations between variables in this study. All physical environmental factors and environmental aesthetic factors exhibited positive and significant correlations (r = 0.23–0.75, $p < 0.01$). In addition, physical environmental factors showed a significant positive correlation with the environmental preference (r = 0.44–0.62, $p < 0.01$). All environmental aesthetic factors appeared to have moderate to large effects on the environmental preference (r = 0.47–0.72, $p < 0.01$). Demographic variables were only significantly correlated with specific physical and aesthetic factors, and showed no significant association with environmental preference. Except for gender, age, and income differences, the remaining demographic variables (place of residence, education level) exhibited either positive or negative correlations with most of the variables.

Table 4. Correlation analysis (Spearman).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1.GEN	-																	
2.AGE	−0.177 **	-																
3.RES	−0.009	−0.017	-															
4.INC	0.021	0.102 *	0.275 **	-														
5.EDU	0.019	−0.123 **	0.391**	0.305 **	-													
6.SE	−0.082	0.096 *	−0.083	−0.027	−0.131 **	-												
7.FA	−0.087	0.046	−0.069	−0.069	−0.122 **	0.725 **	-											
8.VI	−0.078	−0.015	−0.065	−0.078	−0.103 *	0.631 **	0.690 **	-										
9.MA	−0.046	−0.032	−0.132 **	−0.074	−0.159 **	0.703 **	0.691 **	0.677 **	-									
10.MU	−0.107 *	0.057	−0.108 *	−0.074	−0.126 **	0.549 **	0.610 **	0.747 **	0.671 **	-								
11.DI	−0.095 *	0.042	−0.102 *	−0.104 *	−0.164 **	0.528 **	0.576 **	0.671 **	0.639 **	0.717 **	-							
12.UN	−0.031	−0.056	−0.072	−0.048	−0.102 *	0.502 **	0.599 **	0.719 **	0.649 **	0.675 **	0.617 **	-						
13.PR	−0.043	−0.063	−0.021	−0.079	0.028	0.319 **	0.402 **	0.449 **	0.373 **	0.474 **	0.359 **	0.535 **	-					
14.HI	−0.047	−0.003	−0.043	−0.097 *	−0.048	0.384 **	0.503 **	0.613 **	0.505 **	0.611 **	0.563 **	0.612 **	0.571 **	-				
15.HA	−0.059	−0.011	0.002	−0.061	−0.065	0.564 **	0.653 **	0.725 **	0.628 **	0.717 **	0.640 **	0.708 **	0.549 **	0.678 **	-			
16.FA	−0.113 *	0.036	−0.178 **	−0.080	−0.198 **	0.381 **	0.405 **	0.501 **	0.458 **	0.482 **	0.565 **	0.499 **	0.238 **	0.341 **	0.483 **	-		
17.SU	−0.068	−0.010	−0.132 **	−0.080	−0.140 **	0.385 **	0.426 **	0.595 **	0.502 **	0.610 **	0.637 **	0.548 **	0.339 **	0.491 **	0.575 **	0.631 **	-	
18.PRE	−0.065	0.025	−0.058	−0.030	−0.061	0.442 **	0.523 **	0.612 **	0.523 **	0.713 **	0.603 **	0.589 **	0.476 **	0.569 **	0.628 **	0.483 **	0.647 **	-

Note: GEN = Gender. AGE = Age. RES = Residential. INC = Income. EDU = Education. SE = Security. FA = Facility. VI = Visual quality. MA = Maintenance. MU = Multisensory. DI = Diversity. UN = Unspoiled. PR = Protective. HI = Historical. HA = Harmonious. FA = Familiarity. SU = Sublime. PRE = Preference. * $p < 0.05$. ** $p < 0.01$.

3.4. Multiple Regression Models

Table 5 presents the regression results of the three models with preference as the dependent variable. Model 1 serves as the baseline model, including only socio-demographic characteristics. The results indicate that the socio-demographic characteristic variables have a non-significant impact on preference, and the model's explanatory power is poor (Adj $R^2 = -0.003$). In contrast, in Model 2, we incorporate four variables related to the evaluation of physical environmental quality, leading to a significant improvement in the model's power (Adj $R^2 = 0.386$). Specifically, the visual quality has the largest coefficient ($\beta = 0.406$, $p < 0.001$), followed by the maintenance ($\beta = 0.188$, $p < 0.05$) and the facility ($\beta = 0.186$, $p < 0.05$) factors, while security does not show a significant effect ($\beta = -0.090$, $p > 0.05$). Additionally, the education level among the population characteristic variables shows a significant influence on environmental preference in Model 2 ($\beta = 0.095$, $p < 0.05$).

Table 5. Ablation experiments (dependent variable: overall preference).

Variables	**Model 1**	**Model 2**	**Model 3**
Gender	−0.059	−0.024	0.014
Age	0.007	0.037	0.013
Residential	−0.067	−0.053	−0.016
Income	−0.005	0.016	0.049
Education	0.002	0.095 *	0.074 *
Physical environment quality			
Security		−0.090	−0.053
Facility		0.186 *	0.118 *
Visual quality		0.406 ***	−0.031
Maintenance		0.188 *	−0.020
Environmental aesthetic quality			
Multisensory			0.351 ***
Diversity			0.017
Unspoiled			0.024
Protective			0.085 *
Historical			0.117 *
Harmonious			0.056
Familiarity			0.087 *
Sublime			0.245 ***
R^2	**0.008**	**0.398**	**0.603**
***Adj* R^2**	**−0.003**	**0.386**	**0.587**
F	**0.734**	**32.339 *****	**38.553 *** **

Note: Standardized coefficients are reported. * $p < 0.05$. *** $p < 0.001$.

It is worth noting that in Model 3, we included all independent variables, including the eight variables assessing the aesthetic quality of the environment. Model 3 showed a 20.1% increase in information compared to Model 2 (Adj $R^2 = 0.587$). It can be observed that the multisensory factor has the largest coefficient ($\beta = 0.351$, $p < 0.001$), followed by the sense of sublimity ($\beta = 0.245$, $p < 0.001$). In addition, variables related to the perceived value of protection, historical sense, and familiarity also showed a moderate coefficient ($\beta = 0.085$, $p < 0.05$; $\beta = 0.117$, $p < 0.05$; $\beta = 0.087$, $p < 0.05$). Interestingly, the variable representing visual quality, which had the highest coefficient in Model 2 for physical environmental quality, was no longer significant in Model 3 ($\beta = -0.031$, $p > 0.05$). The same situation occurred for the maintenance variable ($\beta = -0.020$, $p > 0.05$). Furthermore, the coefficient of the facility dimension decreased ($\beta = 0.118$, $p < 0.05$).

4. Discussion

This study selected the physical and aesthetic quality factors in line with the environmental characteristics of rural settlements, selected Zhaoxing Dong Village for on-site investigation, and measured tourists' perception and evaluation of rural settlement environmental quality through a designed questionnaire. The impact of environmental quality factors on tourists' preferences was measured via hierarchical linear regression analysis. The overall model results show that all environmental quality factors are significantly positively correlated with preference, and the facility, multisensory, protective, historical, familiarity and sublime factors have a significant impact on tourists' preferences. The analysis of these results and findings as well as the significance of this study will be elaborated upon below.

4.1. Tourists' Evaluation of the Physical and Aesthetic Environmental Quality of Rural Settlements

In the overall evaluation of Zhaoxing Dong Village, there were significant differences in the ratings of physical environmental quality and environmental aesthetic quality. The highest rating in the evaluation of physical environmental quality was for safety assurance (SE = 5.64). The unique settlement lifestyle of the Dong ethnic group contributes to a sense of trust among neighbors, as previous research has shown a correlation between perceived neighborhood safety and trust [64]. Furthermore, safety infrastructure such as streetlights, handrails, and fire hydrants also have some influence on tourists' perception of safety assurance. High-quality lighting conditions and reduced crime rates enhance the sense of safety in the space [65] The scores for infrastructure condition, visual quality of the site, and management and maintenance were similar, with values of 5.47, 5.54, and 5.32, respectively. Regarding infrastructure condition, with the development of urbanization and the intervention of commercial capital, the rise of industries such as catering, accommodation, and tourism in Zhaoxing Dong Village has led to higher-quality service conditions compared to undeveloped Dong villages [66]. This may be the main reason for tourists' high evaluation of village facilities. In terms of the visual quality of the site, the neatly arranged and ethnically characteristic rural wooden structures in Zhaoxing Dong Village enhance the overall visual aesthetics. Among them, the drum tower architecture is the most representative landmark of the Dong ethnic group. Paintings with daily life themes serve as decorations on the buildings, and the complex wooden craftsmanship forms polygonal and multilevel architectural structures. At the same time, Zhaoxing Dong Village is located in an area rich in natural resources, with abundant natural landscapes surrounding the settlement, while the presence of pear and peach trees within the site adds to the attractiveness of Zhaoxing Dong Village. Previous studies have found that natural vegetation can enhance the sense of hierarchy and aesthetics in a space [67]. In terms of management and maintenance, previous research has indicated that the maintenance of buildings and artificial facilities is a dominant factor influencing users' landscape preferences [68]. In Zhaoxing Dong Village, some aging facilities and buildings have not received timely maintenance and renovation, which might be a reason for the lower evaluations from tourists.

In terms of environmental aesthetic quality, the highest rating was given to the perceived value of protection (PR = 6.19), followed by the sense of history (HI = 5.95). Zhaoxing Dong Village has a long history, and its ancestors can be traced back to the Baiyue tribe in the pre-Qin period. Despite the long process of development, they have still inherited an ancient folk culture, architectural culture, and belief culture [54]. These conditions make it difficult for tourists not to give high ratings to the perceived value of protection and the sense of history in Zhaoxing Dong Village. Furthermore, as described earlier, the abundant natural resources surrounding Zhaoxing Dong Village enhance tourists' ratings of multisensory beauty (MU = 5.72), especially in terms of soundscapes. Previous research has extensively studied the soundscapes of Zhaoxing Dong Village, indicating the importance of soundscapes in historic areas [52]. It is worth mentioning the rating for the sense of harmony (HA = 5.71). The street scale in Zhaoxing Dong Village is very suitable for walking ($D/H \approx 0.8$, where "D" represents the width of the road and "H" represents the height of surrounding buildings), and there is a rhythmic increase in space at important nodes, such as the drum tower area ($D/H \approx 1.2$). These spatial proportions have been proven to create the most harmonious and comfortable spatial scale in urban design [69]. Lastly, the lowest rating was given to the sense of familiarity (FA = 4.97). Due to the differences in the residential environment of the respondents, most urban residents were found to be visiting

Zhaoxing Dong Village for the first time, and such rural settlement environments do not exist in cities. Therefore, it is understandable that the rating for the sense of familiarity is quite low.

4.2. The Influence of Environmental Physical Quality and Aesthetic Quality

This study found that most physical environmental quality factors have a significant impact on environmental preference factors ($p < 0.001$), and Model 2 can explain 38.6% of the variance. However, when environmental aesthetic quality factors are introduced as an additional dimension in Model 3, the explanatory power of the model increases to 58.7%. Although significant correlations were found between most physical environmental quality factors and preferences, the significance levels of the physical factors significantly decrease when aesthetic quality factors are introduced as regression variables. This can be attributed to the fact that the correlation between physical environmental quality factors and preference became weak when considering physical and aesthetic qualities simultaneously. A study on the environmental quality of urban parks by Wan et al. (2020) also confirmed this point—that is, in the interaction between users and urban parks, most of the psychological factors have a greater impact on the outcome variables than physical factors [48]. Whether in urban space or rural settlements, aesthetic experience dominates users' perception and evaluation of the environment to a large extent.

In terms of physical environmental quality, the visual quality of the site has the closest relationship with visitor preferences in Model 2 ($\beta = 0.406$, $p < 0.001$). Compared to other perceived physical environmental factors, respondents consider providing better visual aesthetics to be more important, reflecting visitors' pursuit and appreciation of rural environmental landscapes. Some studies have found that vegetation greening in rural environments can provide a healthier breathing environment, promote human physical activity, and evoke positive emotions [42]. Additionally, distinctive regional natural landscapes can help to reduce mental stress from work or study [70], and promote social interaction [71]. Furthermore, there is a significant association between the infrastructure conditions and management maintenance of rural settlements and visitor preferences ($\beta = 0.186$, $p < 0.05$; $\beta = 0.188$, $p < 0.05$). Meeting visitors' basic infrastructure needs such as dining, shopping, accommodation, transportation, etc., is considered to have a significant and positive impact on visitor preferences. Well-developed infrastructure and good management maintenance have a positive impact on visitor experiences [72]. However, it should be noted that the perceived safety of the physical environment does not seem to be significant ($p > 0.1$), which is also the case in Model 3. We speculate that this may be because people's perception of safety in the physical environment is not clear enough. At the same time, village life provides a higher sense of security, and people can more easily establish networks of mutual support and social connections [73].

In terms of environmental aesthetic quality, the factors of multisensory beauty and sublimity are shown in Model 3 to be the most relevant aesthetic quality factors to visitor preferences ($\beta = 0.351$, $p < 0.001$; $\beta = 0.245$, $p < 0.001$). Multisensory beauty is the most reliable aesthetic quality factor across most outcomes. This result supports previous research conclusions demonstrating that visual, auditory, tactile, and olfactory senses play a significant role in stimulating human sensory preferences for the environment [40,44]. For example, in auditory studies, soundscapes have been widely proven to facilitate the recovery from work or study stress, and people prefer to relax in natural environments with the sound of birdsong and flowing water [74]. This indicates that the pursuit of beauty, whether in visual, auditory, or olfactory aspects, largely influences people's emotional preferences. Furthermore, sublimity enhances the visual attractiveness of rural settlements, and grand and historic architecture can generate strong interest among visitors, often resulting in clustering effects [75]. On the other hand, aesthetic factors such as conservation value, sense of history, and familiarity also have a significant impact on visitor preferences ($\beta = 0.085$, $p < 0.05$; $\beta = 0.117$, $p < 0.05$; $\beta = 0.087$, $p < 0.05$). The sense of familiarity has been confirmed in studies on place attachment, indicating that people prefer to live or visit familiar environments [76].

Unexpectedly, some environmental quality factors that were expected to significantly influence preferences did not show a significant effect in this study, such as security, diversity, and sense of harmony. Previous research has demonstrated a close correlation between a sense of security and tourist preferences [60]. However, for tourists visiting Zhaoxing Dong Village for short-term travel, they may have a more positive perception of locally distinctive environmental elements. Therefore, a sense of security might not be a primary factor influencing tourist preferences in this location. Additionally, Ran (2019) proposed that diversity is one of the dominant factors affecting Chinese tourists' landscape preferences [68]. However, this relationship may not be evident in our study site, as tourists generally have higher expectations for unified historical buildings and cultural landscapes in Zhaoxing Dong Village.

Finally, in the demographic variables of Models 2 and 3, education level shows a significant and positive impact on visitor preferences ($\beta = 0.095$, $p < 0.05$; $\beta = 0.074$, $p < 0.05$). This may be because highly educated young individuals tend to have a higher preference for nature [77]. For individuals, the perceived relationship between self-cultivation and aesthetics is more positive for high-education groups than for low-education groups [78].

In summary, this study provides decision-makers with a multidimensional perspective to examine whether rural planning should continue with more diverse facility construction. Additionally, management agencies or managers can conduct more targeted environmental management for the entire rural settlement.

4.3. Study Implications

This study has theoretical and practical significance for the planning and design of rural settlements. While both physical environmental quality and aesthetic quality factors influence people's preferences for rural settlements, many physical environmental quality factors are difficult to fully consider in a comprehensive model. In the process of perceiving rural settlements, environmental aesthetic factors are an essential driving force. People who have positive views of the environment may perceive the environment more positively, thus forming a new understanding and evaluation of the environment. Therefore, it is worth considering adopting intervention strategies that can improve people's cognition of rural settlements. The study of rural environmental quality plays a guiding role in our judgment and will be crucial in future rural planning and design.

In terms of physical quality factors, site visual quality is vital for rural tourism, and efforts to optimize the visual appearance of roads, buildings, natural landscapes, and even vegetation can significantly improve the visual quality of the rural environment. In addition, the construction of rural facilities needs to be paid attention to, and the optimization of local transportation, accommodation, commerce and catering conditions will have a positive impact on the perception and evaluation of tourists. In terms of aesthetic quality factors, providing multisensory experiences is also beneficial in enhancing visitor preferences. In existing sites, introducing sounds of wildlife such as birdsong, frog croaks, or insects chirping can be incorporated. Attracting birds, frogs or insects can be achieved by enriching plant diversity and creating good habitats. For newly built or redesigned sites, it is worth considering exploring and making full use of the existing natural and biological resources to create scenic spots that allow tourists to enjoy a multisensory experience. In addition, planners can reasonably set up garbage treatment stations and sewage treatment facilities according to the wind environment of the settlement, and plant fragrant plants to enrich tourists' sense of smell. Secondly, preserving traditional architectural landscapes and creating an atmosphere with historical and cultural characteristics also play a significant role in improving the evaluation for this setting of visitors. While people come to experience local customs and traditions, they are more inclined to visit well-preserved rural buildings that reflect traditional farming cultures. Therefore, it is very necessary to maintain the local cultural heritage such as historical buildings and landscapes regularly.

The economic benefits brought about by this study should not be overlooked. Governments, managers, and designers can more easily focus on the issues present in rural settlements, providing a good benchmark for resource investment and allocation. Additionally, improving the overall environmental quality of rural settlements can attract a large number of tourists and stimulate local consumption, thereby driving the development of surrounding industries. In the future, this study can be used to guide rural managers and planners to formulate intervention strategies and development plans, and designers can also predict the environmental value of rural settlements through extensive research on user preferences.

4.4. Limitations

This study has certain limitations that should be considered in future research. Firstly, our survey focused only on users of this site, and people who did not visit the study area were excluded. Additionally, the analysis did not consider differences in population perception. Conducting surveys among different groups of people and comparing them among different types of visitors would be beneficial for future research. Secondly, we selected only one village for this study. However, the reliability of the results suggests that the current questionnaire can be applied to other similar study areas. Therefore, more research is needed to supplement the knowledge in this field. Thirdly, due to the complexity of physical and aesthetic quality, which is also influenced by climate change, these scales need further development to encompass a wider range of perceptual items. For example, including temperature perception, perceived brightness, and perceived thermal comfort could be considered in future studies. Fourth, this study employed random sampling, which is a non-probability sampling method and has been widely used in social science research. However, there are some potential limitations to this method, such as the lower probability of underage and elderly groups being surveyed due to the restricted population source of tourists. Also, some populations that are not interested in the topic of this survey are potentially excluded.

5. Conclusions

Through the field investigation of rural settlements with specific environmental characteristics, this study investigates tourists' perception and evaluation of the environmental quality of rural settlements, and analyzes the relationship between environmental quality and tourist preferences. Building upon previous research, two scales were used to measure visitors' perception of the physical and aesthetic quality of rural settlements. The reliability results indicate that the composition of the 12 questionnaire items is acceptable. In the results, we found that eight components significantly influence visitors' environmental preferences in rural settlements. Among them, site visual quality had the highest impact, followed by multisensory aesthetics and sublimity. Infrastructure conditions, management and maintenance, and historical significance had a moderate influence, while factors such as conservation value and familiarity had a relatively minor impact. Factors like safety and security, diversity, undisturbed surroundings, and harmony were found to have a slight influence on visitor preferences. Through this study, we identified key environmental components that affect visitor preferences in rural settlements, deepening our understanding of the factors relevant to rural settlements. Although this study may be limited by the research population, climate change, sampling methods and so on, it still has considerable significance in terms of the current research situation. This research can provide guidance on how to effectively utilize natural and artificial resources in rural settlements and inform the environmental design of rural settlement spaces. Importantly, these findings can benefit managers, policymakers, planners, and designers in their decision-making processes.

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Informed Consent Statement: Oral consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy.

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Assessing Perceived Landscape Change from Opportunistic Spatiotemporal Occurrence Data

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Abstract: The exponential growth of user-contributed data provides a comprehensive basis for assessing collective perceptions of landscape change. A variety of possible public data sources exist, such as geospatial data from social media or volunteered geographic information (VGI). Key challenges with such "opportunistic" data sampling are variability in platform popularity and bias due to changing user groups and contribution rules. In this study, we use five case studies to demonstrate how intra- and inter-dataset comparisons can help to assess the temporality of landscape scenic resources, such as identifying seasonal characteristics for a given area or testing hypotheses about shifting popularity trends observed in the field. By focusing on the consistency and reproducibility of temporal patterns for selected scenic resources and comparisons across different dimensions of data, we aim to contribute to the development of systematic methods for disentangling the perceived impact of events and trends from other technological and social phenomena included in the data. The proposed techniques may help to draw attention to overlooked or underestimated patterns of landscape change, fill in missing data between periodic surveys, or corroborate and support field observations. Despite limitations, the results provide a comprehensive basis for developing indicators with a high degree of timeliness for monitoring perceived landscape change over time.

Keywords: spatial–temporal; landscape change; opportunistic data; photo content; perception

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1. Introduction

It is common to think of landscape as a specific arrangement of objects in space. These objects can then be measured, inventoried, and mapped for purposes of environmental planning and natural resource management. To shift the perspective to a process-oriented view, anthropologist Tim Ingold [1] coined the term landscape temporality in 1993. According to Ingold, this concept encompasses both the human viewer component and the physical manifestation of objects in space and time. Landscape temporality can therefore refer to both human and environmental change. This is similar to concepts in landscape and urban planning, where "experiential" approaches aim to describe how people perceive and interact with the landscape [2]. It is generally accepted that both human and environmental change can significantly influence human–environment interactions and the perceived meaning and value of landscapes [3]. However, the human viewer component in particular complicates the assessment of landscape scenic resources. Landscape and environmental planners need to assess not only physical changes (including ephemeral features) but also how people respond to these changes, which in turn affect landscapes. This includes temporal characteristics, trends, and collective perceptions of landscape change. Consequently, both the human viewer and the landscape are important issues in the assessment of scenic resources. In recent years, however, search and ranking algorithms and the global spread of information increasingly influence the behavior of large groups of people [4]. This affects collective engagement and interaction with the landscape and its scenic resources. For this reason, social media and the dissemination of information have become a new component that planners need to consider.

To systematize these three components (the environment, the human viewer, and information technology) for landscape change assessment, we propose the application of the social–ecological–technological system (SETS) framework [5] to temporal geosocial media analysis. To demonstrate and discuss a variety of situations, we examine temporal patterns from five platforms (Reddit, Flickr, Twitter, Instagram, and iNaturalist) and for five case studies. In particular, we interpret the results from a human-centered perspective, with the aim of disentangling the human viewer component from several other superimposed patterns in the data, such as algorithmic bias, platform dynamics, or shifting perceptual preferences. The results can help to corroborate or complement traditional scenic resource assessments. The presented approach can also extend the means to include newer phenomena resulting from changing communication patterns in a globally connected world.

2. Literature Review

In an attempt to improve the empirical assessment of ephemeral landscape features, Hull and McCarthy [6] proposed a concept they called "change in the landscape". While the authors give a specific focus to wildlife, they describe a wide range of processes associated with change: "[. . .] day changes to night, autumn to winter and flowers to fruit; there is plant succession, bird migration, wind, rain, fire and flood [. . .]" (ibid., p. 266). These changes are characterized by nine types, such as slow changes (gentrification of neighborhoods, growth of vegetation), sudden changes (weather fluctuations), regular changes (seasonal in plants, animal migration, sunrises), frequent (presence of wildlife, wind, sounds), infrequent (fire, floods), long duration (buildings, roads, consequences of natural disasters), medium duration (harvesting of trees, seasons), ephemeral–irregular, occasional, and periodic (wildlife, weather, hiking, evidence of other hikers). In their conclusion, the authors warn that ignoring these conditions leads to biased assessments of landscape quality. In practice, however, common temporal assessments continue to focus on physical manifestations of change, such as those observed in biotopes [7], which are often assessed using remote sensing technologies [8].

A number of approaches investigate people's perceptions, attitudes, and responses to environmental change and how people engage with the landscape over time [9]. With the emergence of large collections of user-generated content shared on the Internet, several studies have attempted to assess temporal aspects. Juhász and Hochmair [10] compared temporal activity patterns between geolocated posts shared on Snapchat, Twitter, and Flickr and found that the different active groups on these platforms are responsible for significant differences in the observed spatial patterns. A better understanding of the source and nature of these differences has become a central focus of research around volunteered geographic information (VGI). Paldino et al. [11] studied the temporal distribution of activity by domestic tourists, foreigners, and residents in New York City, analyzing daily, weekly, and monthly activity patterns and differences between these groups. Mancini et al. [12] compared time series collected from social media and survey data. They concluded that day trips have the greatest impact on the differences between survey and social media data. Tenkanen et al. [13] showed how Instagram, Flickr, and Twitter can be used to monitor visitation to protected areas in Finland and South Africa. Their findings suggested that the amount and quality of data vary considerably across the three platforms.

In a relatively new direction, ecologists are increasingly relying on unstructured VGI for biodiversity monitoring [14]. Rapacciuolo et al. [15] demonstrated a workflow to separate measures of actual ecosystem change from observer-related biases such as changes in online communities, user location or species preferences, or platform dynamics. In particular, they found that trends in biodiversity change are difficult to separate from changes in online communities. In a recent study, Dunkel et al. [16] examined reactions to sunset and sunrise expressed in the textual metadata of 500 million photographs from Instagram and Flickr. Despite significant differences in data sampling, both datasets revealed a strong consistency in spatial preference patterns for global views of these two events. Platform biases were observed in locations where user groups differed significantly, such as the Burning Man festival in Nevada. The festival location ranked second globally for sunrise viewing on Instagram, while Flickr users shared very few photos, a pattern that is explained by the different user compositions of these platforms.

As becomes obvious with the above review, a key task in analyzing user-generated content is to reduce bias in the data to increase representativeness. Bias can include factors such as uneven data sampling affected by population density, or highly active individual users skewing patterns through mass uploads, as well as changes in platform incentives that affect how and what content is shared [12]. There are a number of methods that can help compensate for these effects. However, these methods can also introduce bias and further reduce the amount of data available, making interpretation more difficult. For this reason, ref. [15] divide approaches into two broad categories that are not mutually exclusive but tend to have opposite effects: filtering and aggregation. Filtering increases precision, which helps to derive more reliable and useful inferences but also tends to reduce the available variance, richness, and representativeness of the data. Aggregation, on the other hand, minimizes bias in the overall data by, for example, increasing quantity through sampling from a larger, more representative number of observers and by integrating data from different platforms. This comes at the expense of precision. Aggregation and filtering approaches can be combined [17].

A gap in the current literature is how to systematize the application of filtering and aggregation approaches for new studies. The number of possible biases in data is large (e.g., [14]), and it is not possible to know a priori which biases affect the data. There is a lack of a categorization scheme to help understand the phenomena that affect sampling at specific times and places. A first step in this direction is the consideration of any user-generated data as "opportunistic" sampling and the contributing users as "observers". Both terms are increasingly used in biodiversity monitoring [14,18]. Opportunistic in this case refers to the degree to which data are sampled without predefined systematic contribution rules or objectives. The classification is not abrupt, and a continuum of platforms exists between fully standardized and rigorous survey protocols at one end (e.g., the United Kingdom Butterfly Monitoring Scheme [19]) to semi-structured data (iNaturalist or eBird as VGI that is aimed at collecting data for a specific purpose), to fully crowdsourced data (Flickr, Twitter, Reddit, Instagram as geosocial media) [20]. The ranking of platforms along this continuum can be judged by the homogeneity of contributing user groups and contribution rules. In summary, the above research suggests that opportunistic data tend to be better for inferring users' subjective values, including individual preferences for activities and observational behavior, making them suitable for assessing landscape perception and scenic resources.

This openness typically results in larger volumes of observations than are typically available from more systematized field surveys but also leads to more biases that can negatively affect the reliability and validity of the data. Proposed solutions to reduce bias in species monitoring are (1) reverse engineering the "survey structure", (2) finding the lowest common denominator for comparison, (3) modeling the observation process, and (4) comparing to standardized data sources [15]. Applying these solutions to landscape perception, however, requires a broader set of considerations for disentangling results. While ecological changes are critical for landscape and urban planners, changes in the observer and the observation process itself are equally relevant. The latter covers effects introduced by the use of global social media and information spread. Examples include mass invasions [4] and algorithmic bias [21], which can have negative effects on landscapes and how they are perceived.

This study presents five case studies. We discuss three main areas in which change can occur: ecological, social, and technological. The domains are taken from the SETS framework. They are used to systematize biases in the case studies and to assess perceived landscape change from different perspectives. Rather than looking at a single dataset in detail, the cross-section allows us to test the system under different parameters. In the literature cited above, the effects of technology are often subsumed under distributional measures of the social domain or treated as one of many different biases affecting data collection. Explicitly considering technology as an independent component helps us systematize the analysis process and better distinguish important levers for biases found in the data. We show how the framework can help analysts disentangle the three domains when interpreting and making sense of temporal patterns in community-contributed opportunistic data sources.

3. Materials and Methods

3.1. Framework for Analysis

The SETS framework is a system consisting of three poles, the social (S), ecological (E), and technological (T) [22]. So-called couplings exist between these poles. Couplings can be thought of as a "lens" for understanding the dynamics between different parts of complex ecosystems. Perceptions of landscape change are part of such a system. To date, research on landscape perception has mainly focused on two of these poles: the physical landscape and the perceiving human (see [23]). The third technological pole of the SETS framework has usually been subsumed under physical landscape assessment, which may include changes such as infrastructure. However, Rakova and Dobbe [24] emphasized that algorithms have become a critical part of the technological pole. Algorithms increasingly affect the interactions between society and ecosystems on a global scale. From this perspective, it makes sense to consider technology as a separate third component. Using geosocial media or VGI as an interface for data collection means that technological couplings can be identified as imprints in data (shown on the right side of Figure 1). Conversely, people communicating on these platforms use their senses and social context (the social dimension, S) to choose what to share and when to share it. Lastly, scenic resources and the environment (the ecological dimension, E) provide incentives that affect people's agency and their ability to perceive and respond in a particular way.

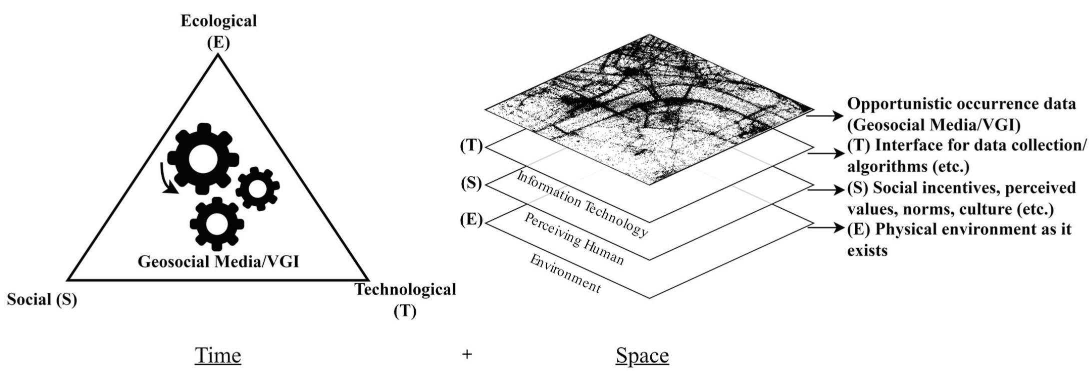

Figure 1. SETS framework for separating three types of couplings influencing opportunistic data collection through geosocial media and VGI over time (**left**) and space (**right**).

At the same time, more complex feedback loops exist between these poles that require special attention. In particular, technological phenomena such as algorithms influence individual social–ecological interactions [25]. People gather information from all sources when making travel arrangements, for example. Their choices may be influenced by the physical characteristics of the landscape, such as scenic quality, as an ecological coupling (hereafter referred to as E), or by reports, reviews, and recommendations from other travelers, which can be seen as an example of a social coupling (S). Such a spatial discourse has effects over time on perceived values, norms, or the ways cultures perceive scenic beauty [2]. Finally, algorithms that promote some information while downgrading others can be described as a technological coupling (T). Especially in the latter case and for geosocial media, many algorithms and platform incentives have known and unknown effects on user behavior [26,27]. The sum of these experiences defines how information about the environment is perceived and communicated. Geosocial media and VGI, therefore, can have a profound influence on long-term dynamics. Through repetition and reinforcement, algorithmic couplings increasingly manifest as actual changes in the social or ecological domain. Van Dijck [25] already argued that networks such as Flickr "actively construct connections between perspectives, experiences, and memories" but also warned that "the culture of connectivity [. . .] leads to specific ways of 'seeing the world'" (p. 402). For example, by rewarding particularly stunning landscape photographs with "user reach" on social media, some landmarks are already under unusual visitation pressure [4].

Figure 1 illustrates geosocial media and VGI as a core component and as indistinct from SETS. This concept helps to consider these algorithms together with their social (including institutional) and ecological couplings that define the broader ecosystem in which they operate [24,28]. To draw useful conclusions and derive actionable knowledge, planners need to assess all three poles. However, approaches to disentangling the effects of these poles vary widely depending on the data source and analysis context. To explore these different analytical contexts and data characteristics for assessing perceived landscape change, we use data from five platforms in five small case studies. The case studies illustrate a variety of tasks, challenges, and pitfalls in early exploratory parts of analyses. We discuss these case studies from a SETS perspective. The discussion is sorted based on the complexity of identified data couplings, from less complex to more complex.

3.2. Data Collection and Preprocessing

Table 1 lists platforms and number of observations collected for each study. Data collection for these studies was performed using the official application programming interfaces (APIs) provided by the platforms. APIs are challenging to work with. They often change on a weekly or monthly basis, are difficult to fully sample, and are often incompletely documented. For example, the Instagram, Reddit, and Twitter APIs have changed in ways that would make it very difficult or impossible to retrieve the data that were collected for this study again and in the same form. Therefore, transparency, reproducibility, and reusability are critical issues in this area of research. We follow a workflow outlined in [29] that allows us to share the data collected from the APIs without compromising user privacy. Based on this workflow, the data have been transformed into a privacy-friendly format that allows quantitative analysis without the need to store raw data. As a result of this data abstraction process, all measures reported in this paper are estimates, with guaranteed error bounds of $\pm$2.30%. Only publicly shared content was retrieved. With the exception of the Reddit data, we only selected content that was either geotagged or contained some other form of explicit reference to a location or coordinate. To reduce the effort of cross-platform analysis, we mapped the different data structures and attributes of all platforms to a common structure for comparison[1]. To assess temporal patterns, we used either photo timestamps (Flickr), time of observation (iNaturalist), or post-publication date as a proxy (Twitter, Instagram, Reddit). Below, we keep the discussion of data collection and processing steps to a necessary minimum and refer readers to Supplementary Materials S1–S10 for commented code, data collection, processing, and visualization.

The first study focuses on data from Instagram, as a single data source, and a specific phenomenon related to landscape change that is observed at 13 selected vantage points across Europe (see S1). The study captured metadata from 998,800 photographs from 40 Instagram places between 2007 and 2019. Because multiple Instagram places can refer to the same vantage point, we applied manual disambiguation to assign Instagram places to vantage points. In the second study, we looked at Reddit, a discussion platform that does not support explicit georeferencing. However, spatial information can be inferred, for example, from subreddits that refer to different spatial regions. We manually matched

46 subreddits related to US national parks and collected comments and posts from 2010 to 2022 (S2–S5). This dataset contains 53,491 posts and 292,404 comments. Due to significant differences in data availability, we limit our analysis to the 20 national parks that receive the most communication exposure. The third study focuses on a single ecological phenomenon (cherry blossoming) and examines seasonal and long-term variation across two platforms (S6). The data collected include metadata for 100,700 photos from Flickr and 1.6 million tweets from Twitter. The fourth study illustrates cross-platform analysis by sampling and aggregating data from Instagram, Flickr, Twitter, and iNaturalist for 30 biodiversity hotspots in Germany. The total number of photos and observations is 2,289,722. In this case study, we do not apply any filtering techniques, and the results show the absolute frequencies of photos, tweets, and animal and plant observations, respectively (S7). In the last case study, we look at global observations of the Red Kite (*Milvus milvus*) and use a variety of filtering techniques to examine temporal patterns (S8–S10).

Table 1. Overview of case studies and collected data.

Case Study	Instagram	Flickr	Twitter	Reddit	iNaturalist
(1) "Mass invasions"	998,800 2007–2019	/	/	/	/
(2) "National parks"	/	/	/	345,900 2007–2023	/
(3) "Cherry blossoms"	/	100,700 2007–2018	1.6 M 2007–2018	/	/
(4) "Biodiversity hotspots"	997,200 2007–2020	915,800 2007–2022	221,100 2007–2022	/	117,000 2007–2022
(5) "Red Kite"	/	22,080 2007–2023	/	/	9 M 2007–2023

3.3. Signed Chi Equation

Specifically for the last case study, we apply the signed chi normalization to temporal data. This equation was originally developed by Visvalingam [30] to visualize overrepresentation and underrepresentation in spatial data.

$$chi_t = \frac{((obs_t * norm) - exp_t)}{\sqrt{exp_t}} \qquad norm = \frac{\Sigma_{exp}}{\Sigma_{obs}}$$

Applying this normalization allows analysts to distinguish properties of filtered subsets of data from phenomena or biases found in the entire data set [30]. The two components can also be described as a generic query (*expected*) and a specific query (*observed*). A specific query might be the frequency of photographs related to a particular topic or theme (e.g., all photographs of the Red Kite). A generic query, on the other hand, ideally requires a random sample of data. Observed and expected values are usually evaluated for individual "bins", which can be spatial grid cells or temporally delimited time periods or intervals. Based on the global average ratio of frequencies between observed (Σ_{obs}) and expected (Σ_{exp}), individual bins are normalized (*norm*). Positive chi values indicate overrepresentation and negative values indicate underrepresentation of observations in a given area or time interval (chi_t). The randomness of the generic query is typically difficult to achieve due to the opaque nature of APIs. For example, it is not always clear how data have been pre-filtered by algorithms before being served to the user [16]. The easiest way to ensure randomness is to sample all data from a platform. For Flickr and iNaturalist, this was possible, and all geotagged photos and observations were queried for the period from 2007 to 2022. The resulting dataset we use for "expected" frequencies consists of metadata of 9 million iNaturalist observations. Observed frequencies are based on 22,075 Flickr photos and 20,561 iNaturalist observations. All data and code used to generate the graphs are made available in a separate data repository [31].

4. Results and Discussion

4.1. Mass Invasions (Instagram)

For the first case study, we looked for a phenomenon called "mass invasions" by Oian et al. [4], which refers to landscape changes triggered by technology and the use of geosocial media. We expected that such a phenomenon would be easier to identify in the data collected from geosocial media and VGI, since the phenomenon under observation and the interface for data collection are closely related. We focused on a selected list of 13 scenic places in Europe that were known to be affected. This analytical context is part of a master's thesis by Tautenhahn [32]. The term is used to describe a sudden increase in visitors that cannot be explained without taking into account geosocial media and the global spread of information. Here, the effect of people crowding certain places can be described as primarily belonging to the social (S) domain. Crowding existed before social media (see [33]). Likewise, without the existence of scenery and beauty at these locations, mass invasions might not have occurred in the first place. Thus, the ecological (E) and social (S) domains can be seen as a necessary backdrop for this coupling. However, platforms, algorithms, and the Internet as technology (T) seem to reinforce and incentivize certain behaviors that produce a particular outcome in these places.

Data collection and analysis for this study presented relatively few challenges. Claudia Tautenhahn contributed a list of potentially affected places, based on a priori knowledge that she gained from literature and field observations. Because Instagram enables place-based communication through a named gazetteer of user-contributed places, these places could be used to directly query and filter data. For the 13 given locations and 40 assigned Instagram places provided by Tautenhahn, we retrieved all posts, starting in 2019 and going backward in time. To emphasize, the data collection was performed by the authors of this article, and the visuals presented here were generated independently of the master's thesis. Tautenhahn's thesis is based on the same data and includes additional qualitative surveys and interpretations, which we cite accordingly. Figure 2 shows time series visualizations for a subset of four of these places. The graphs were generated based on the total monthly Instagram post volume. In addition, the single month with the highest frequency of posts and the 12-month moving average are shown.

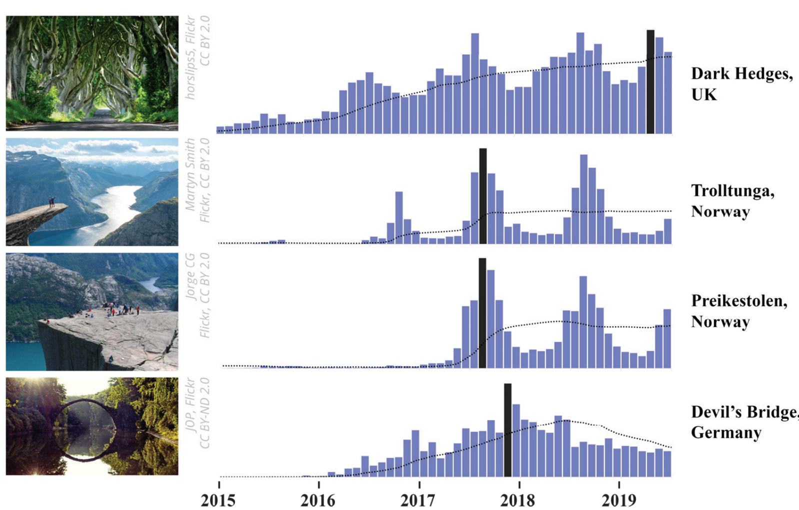

Figure 2. Time series visualization (Instagram) for selected vantage points in Europe that are known to have shown "Mass invasions". Months with the highest number of visits are highlighted in black. The 12-month moving average is shown as a dotted line. See Appendix A, Figure A1 for visualizations of all 13 assessed vantage points.

To begin exploring questions of why and how, a common first step in interpreting such graphs is to formulate hypotheses [34]. Comparing relative differences is an important key task, as absolute post volume is not a robust and reliable measure [35]. We accounted for this fact by scaling the y-axes between the minimum and maximum values in Figure 2 and by omitting absolute values. Based on visual comparison, the relative differences between the four graphs can be grouped into three categories. Dark Hedges, a famous avenue of old beech trees in the UK made famous by the TV series "Game of Thrones", shows a continuously increasing trend that also starts relatively early compared to the other locations. In contrast, the two viewpoints Trolltunga and Preikestolen in Norway both show a strong seasonal trend, peaking in the summer months. For these two sites, the first significant peak in Instagram post volume also appeared relatively late in 2016–2017. As an outlier, the Devil's Bridge in Germany, known for its distinctive water reflection that forms a full circle, shows an increasing trend in Instagram posts that peaks in the fall of 2017 and then suddenly declines. In contrast to the other three locations, the Devil's Bridge graph shows no noticeable seasonal patterns.

The formulation of useful hypotheses typically requires the consideration of additional data. For Devil's Bridge, a review of infrastructure changes reveals that the bridge was undergoing renovations from 2018 to 2021 [32] (p. 55), a finding that can explain the declining trend in Instagram photos. In other words, the opportunity to take stunning photos of the bridge and generate "reach" on geosocial media was severely limited during this time period. This simple and obvious relationship can be described as a coupling from the SETS framework. The construction, as a (1) technological phenomenon, affects the (2) social dimension of visitors' agency to take photos of a given scene. The motivation to take these photos (3) is perhaps related to the platform, which incentivizes the reproduction of idealized photos that generate as many comments, likes, or reshares online as possible [36]. A similar social–technological incentive could also be at work at Dark Hedges, further fueled by the global spread of information through geosocial media, as an algorithmic–technological coupling that reinforces these trends. Such hypotheses would need further confirmation through, e.g., questionnaires. In an interview by Tautenhahn [32] at Dark Hedges, a couple confirmed the relationship between the TV series and their motivation to visit the avenue (transcript, p. 201):

I: So what were your motives to come here? Your reasons?

P 1: Ahm. . .

P 2: Of course the movie.

[. . .]

I: (Laughs) And what did you expect when you came here?

P 1: Ahm, basically something like that. [Okay] A little bit overcrowded. [Yeah. Okay] Yeah. But beautiful landscape of course.

Options for confirmatory analysis also include internal consistency checks, such as regression analysis or comparing the consistency of individual ratios. For example, for Dark Hedges, Tautenhahn [32] examined the proportion of posts containing hashtags related to the TV series (#gameofthrones, #GoT, #kingsroad) over time. Her results show that the ratio of posts containing at least one of these hashtags increased continuously up to 55% in April 2015 and remained relatively stable thereafter, a finding that can be used to support hypotheses and gain confidence in the data. Similarly, the small peak for Devil's Bridge in December 2016 can be linked to Lorenz Holder winning the Red Bull award with a photo of the bridge and its reflection (ibid., p. 54), an event that may have originally triggered reactions on geosocial media.

4.2. National Parks (Reddit)

Clearly delineated contexts with a single phenomenon and pole as a common denominator, as in the first example, are unfortunately rare in landscape change assessment. Many contexts require the study of landscapes at smaller scales, often covering large regions with many phenomena and a variety of perceiving user groups. This not only requires more effort to query, filter, and map data but also reduces the specificity of hypotheses that can be identified from exploring patterns. To illustrate such a context, we selected a list of 20 Reddit subreddits related to US national parks for the second example. The list of subreddits is comparable to the list of Instagram locations in the first example. Both gazetteers allow analysts to examine a set of locations or regions (E) from the perspective of a selected group (S) of users on a particular platform (T). Figure 3 shows the average monthly post and comment volume for the Reddit data for each park. The graphs are stacked into a single visualization. This type of visualization, also known as a Joyplot, is particularly useful for comparative analysis of changes in distributions over time [37]. The Joyplot sorts the graphs for the national parks in descending order of importance based on the average volume of data per month. To avoid obscuring parks with less communication, parks with the most comments are shown in the background.

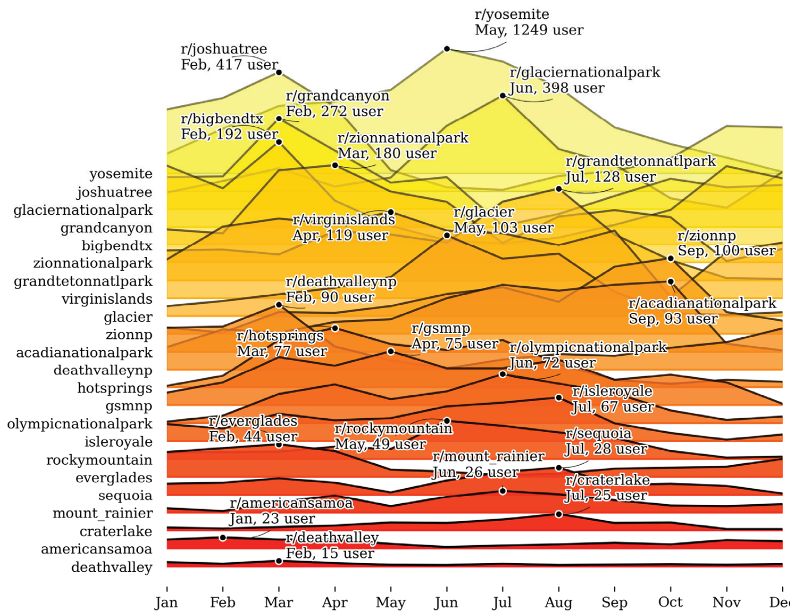

Figure 3. A Joyplot visualizing seasonal communication trends for selected national parks based on unique user counts from community-led subreddits. "Mountain peaks" are used as a metaphor for the volume of monthly patterns that deviate from the norm (the average monthly communication frequency for each park). See Appendix A, Figure A2 for individual visualizations of posts and comment volume per subreddit.

Contrary to what one might expect, the ranking of Reddit parks (the order of ridges in Figure 3) does not match the rankings reported by official visitation statistics. For example, Great Smoky Mountains National Park is ranked #1 in official visitation statistics, while it is ranked #14 based on the volume of posts and comments on Reddit. However, when this overall bias is ignored, the monthly post volume for individual parks actually confirms our expectation that seasonal preferences and limitations for viewing scenic resources are reflected in communication trends. For example, Yosemite, Glacier, and Grand Teton national parks are difficult to visit in the winter due to harsh weather conditions. This is also evident in Reddit's communication trends. Similarly, Joshua Tree, Zion, Grand Canyon, Big Bend, and Death Valley national parks are popular during the winter season when temperatures are more moderate.

However, just because people communicate and share photographs online does not necessarily mean (1) that they visited a national park, (2) that they perceived scenic resources, or (3) that the quality of their experience was positive or negative. The strength of the coupling between visual perception and collected data varies based on the interface that is used for data collection [36]. This also applies to data collected from different social media platforms. Flickr's metadata, for example, often contains relatively direct links to the visually perceived environment, through photo timestamps or GPS coordinates [27]. In contrast, posts on X (formerly Twitter) are frequently published retrospectively and do not necessarily refer to the referenced geolocation [38]. From the perspective of visual resource assessment, these biases can be seen as a detrimental effect. It can also be seen as an opportunity to investigate different forms of environmental perception. Reddit, for instance, incentivizes a particular form of communication that regularly produces extensive discussion on a specific topic [39]. This is evident when looking at a small subset of four Reddit post titles for Yosemite selected from Supplementary Materials (S2):

1. What equipment do I need for Vernal Fall in April?
2. Does group size of 1 help half dome lottery chances?
3. Yosemite Valley with little kids—in the snow—Trip Report
4. Mirror Lake today before the snow

One might wonder what "equipment" (1) has to do with appreciating the beauty of Vernal Falls. Or how and why the "Half Dome Lottery" (2) affects the visitor experience, or the effect of traveling with or without small children on the perception of the valley (3). These questions may be only indirectly related to actual visual changes observed in the landscape, but they can be critical for exploring dynamic relationships and making sense of preference factors. Particularly, these discussions can be used by visual resource specialists to examine three independent forms of landscape perception: (1) pre-visit expectations, (2) on-site, in situ perceptions and experiences, and (3) post-visit retrospective reports and abstracted memories of scenes.

Here, considering Reddit as a separate technological factor or lens can help draw attention to the strengths and weaknesses of different platforms. Individual platform features and algorithms result in a specific set of written and unwritten contribution rules, restrictions, and incentives that affect the opportunistic contribution of data [10]. These circumstances create a self-selection bias for contributing users. Hargittai [39] identifies several of these for Reddit, including gender bias (more men than women), education bias (more middle to higher education), and a bias toward users from urban areas. Biases generally limit representativity. They may also explain why certain parks receive more (e.g., Yosemite, Yoshua Tree) or less (e.g., Death Valley, Everglades) attention on Reddit than is observed in field surveys. Many biases are difficult to assess systematically as they are a consequence of complex couplings between the social and technological domains. Depending on the context of the analysis, these factors limit the ability to draw valid and accurate conclusions, such as for comparing different park uses. Conversely, correlations between the seasonality of platform use and the ecological characteristics of individual parks indicate an easier-to-identify coupling. This may offer options for developing indicators for monitoring perceived landscape change for individual parks.

4.3. Cherry Blossoms (Flickr, Twitter)

The first two case studies show a mix of ecological, technological, and social dynamics in data patterns. Is this always the case? To illustrate the impact of a single phenomenon across multiple platforms, we considered observations of cherry blossoms (E) shared on Twitter and Flickr. Our hypothesis is that, under certain circumstances, global communication should be closely linked to actual ecological change. Cherry blossoms can be seen as one of the many phenomena that Hull and McCarthy [6] categorized under landscape change (see Literature review). Our expectation was that the regularity and seasonal appearance of cherry blossoms each spring should allow us to better observe changes in patterns related to the other two SETS dimensions. For example, cultural changes (S) could lead to a steady increase in perceived importance that is visible online (T); or unexpected fluctuations in the regularity of reactions could draw attention to trends and events not captured so far. Figure 4 illustrates the global volume of tweets and Flickr photographs that contain references to cherry blossoming from 2007 to 2018. For both Flickr and Twitter, we used the same query to semantically filter content:

$$('\text{cherry}'\,AND\,('flower'\,OR\,'blossom'\,OR\,'sakura'))\;IN\;(post.hashtags\;OR\;post.post\_title\;OR\;post.post\_body)$$

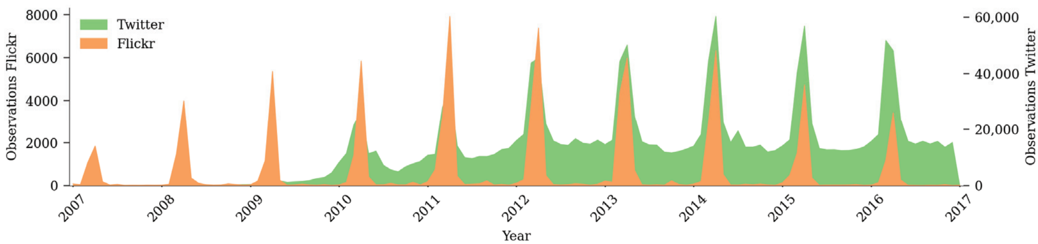

Figure 4. Global Flickr and Twitter cherry blossom-related online communication.

We explicitly limited our query to English terms and the Japanese word *sakura*, accepting a possible language bias. Furthermore, while we restricted the Flickr query to geotagged content, we left the Twitter query unrestricted due to the limited availability of only 1% of geotagged tweets.

Three key observations can be made. Firstly, the regularity and strong delineation of peaks each spring can be observed for both Twitter and Flickr. This underpins the overarching ecological bias of the phenomenon. Blossoms are visually sensed. The possibility to physically observe cherry blossoms is further limited to a brief period each year. Confirmation of this aspect in the graph (Figure 4) can be seen as a consistency check for the data collection process. In other words, both Twitter and Flickr capture at least some of the experiential dynamics of perceiving cherry blossoms as a visible change in the landscape. Secondly, and perhaps more interestingly, Twitter and Flickr patterns differ (T). While Flickr's photograph volume is mainly limited to the short periods when blossoms are actually visible (February through April), the data from Twitter feature a more continuous volume of tweets throughout the year. A possible explanation could be the unequal platform impact on the data collection process. Photographs can be considered as shared digital artifacts of landscape perception [40]. Taking a photograph typically requires active observation and presence [41]. We likely further substantiated this coupling by limiting our Flickr query to geotagged content only. This is not the case for users of X (formerly Twitter), who also use non-geotagged and text-only tweets that only metaphorically refer to cherry blossoms. A look at a small subset of the collected data can support this assumption and reveal other differences between the two platforms.

Twitter:

1. wondering why the cherry blossom tourists have to take the Metro during rush hour
2. Ugh cherry blossom fest traffic hell. Avoid the downtown mall
3. The Sakura flowers are expected to be on its full bloom tomorrow, can't wait to just sit under the Cherry Trees
4. LED Cherry Blossom Tree—National Deal, Special 1

Flickr:

1. This looked so nice in the sunlight. A whole tree filled with big clumps of cherry blossom and this little clump was leaning out into the sunlight.
2. This is our Cherry tree in full bloom a couple of months ago, before the wind blew the blossom away. You can't tell from this how overgrown the garden is. Can't comment at moment.

Interestingly, while the two selected Flickr photo descriptions are positive, half of the shown tweets also refer to negatively perceived events related to the cherry blossoms. Technology (T) and the way communication works on X seem to motivate users (S) to report on negative experiences as well. Based on our limited observation, the same cannot be said for Flickr, where users rarely share negatively perceived content. Furthermore, a tweet referencing the "LED Cherry Blossom Tree" (a corporate advertisement) illustrates a strong bias toward the intertwining of cherry blossoms in culture and technology. This observation of occurrence is almost decoupled from its ecological origin (E) and would be considered noise that must be excluded for any analysis of actual landscape change. These observations may mean that analysts need better filtering procedures to consider Twitter as a valid data source for studying visual perception or to exclude the platform's data altogether. Empirical testing could confirm and support these subjective observations, which was not performed in this paper. Finally, the regularity of the cherry blossoms and the global data collection also allow us to observe underlying platform trends [42]. Flickr's overall popularity increased until 2012–2013, with a downward trend in users since then (Figure 4). The rise of Twitter, on the other hand, appears to be slightly offset, with a noticeable peak in 2014, according to our data. These technological artifacts distort interpretation over longer periods and must be accounted for, which we demonstrate in the last case study (Section 4.5).

4.4. Biodiversity Hotspots (Flickr, Twitter, iNaturalist, Instagram)

As becomes obvious, comparing data from multiple platforms is particularly useful for identifying and separating technological (T) impacts from ecological (E) and social (S) phenomena. To illustrate this utility, our next case study explicitly aimed to collect data from many platforms and for a variety of regions of scenic interest. Using data from Flickr, Twitter, iNaturalist, and Instagram, we examined the variance in seasonal user frequency for five platforms and for 30 biodiversity hotspots in Germany (see Appendix A, Figure A3). Figure 5 shows a subset of three hotspots as stacked frequency bar plots. All hotspots show divergent patterns, with user frequency varying significantly over the year and across platforms. For example, the "Ammergebirge, Niederwerdenfelser Land und Obere Isar" (Hotspot 2) appears to be a popular holiday destination at the turn of the year and for Instagram (e.g., winter sports tourism). At the same time, this region shows a relatively constant flow of visitors across all platforms in all seasons. In contrast, the "Limestone and Volcanic Eifel" (Hotspot 14), a region known for its attractiveness for nature lovers and hikers, seems to attract a disproportionately high number of animal and plant observers, especially in summer (iNaturalist), according to our data. Other regions, such as "Mecklenburg-Brandenburgisches Kleinseenland" (Hotspot 25), are primarily characterized by summer tourism. Many of the remaining hotspots, available in Appendix A, Figure A3, can also be assigned to these three categories. In our data, Twitter and Instagram tend to show the least variation in frequency throughout the year. In comparison, iNaturalist and Flickr users seem to share more data, relatively speaking, during the summer months.

Looking at these graphs, it is clear that different platforms (T) promote different user groups (S) with different interests. These interests influence how and when data are shared. For example, for hotspot 25, characteristic lakes provide a number of ecosystem services (E) for well-being that attract families and young people during the summer months. On the other hand, rare species are difficult to observe with children playing nearby, which may explain the underrepresentation of iNaturalist and the overrepresentation of Flickr observations in this region. Similar couplings between ecology (E) and social preferences (S) can be identified for the other hotspots. It would be natural to assume that older people and species and plant observers, seeking quiet recreation during the summer months, are more likely to avoid the busy family tourism in hotspot 25. Instead, hotspot 14 may offer a set of features that better correlate with the interests of these groups, resulting in an overrepresentation of iNaturalist data in this region. Finally, hotspot 2 is located in a region bordering the Alps, which is popular for group travel. This characteristic overlaps well with group activities such as skiing or snowboarding. New Year's Eve is a singular event of particular importance for this group, which is shown as a significant peak for January in our data. These patterns can be used to understand environmental justice and socio-spatial inequality in decision-making [24]. The regularity and persistence of these seasonal trends can further support monitoring changes over time. In these cases, cross-platform sampling can reduce bias and increase the trustworthiness of the data. Unfortunately, rigid spatial delineation of hotspots requires coordinates of sufficient accuracy, which are only available from a limited number of platforms.

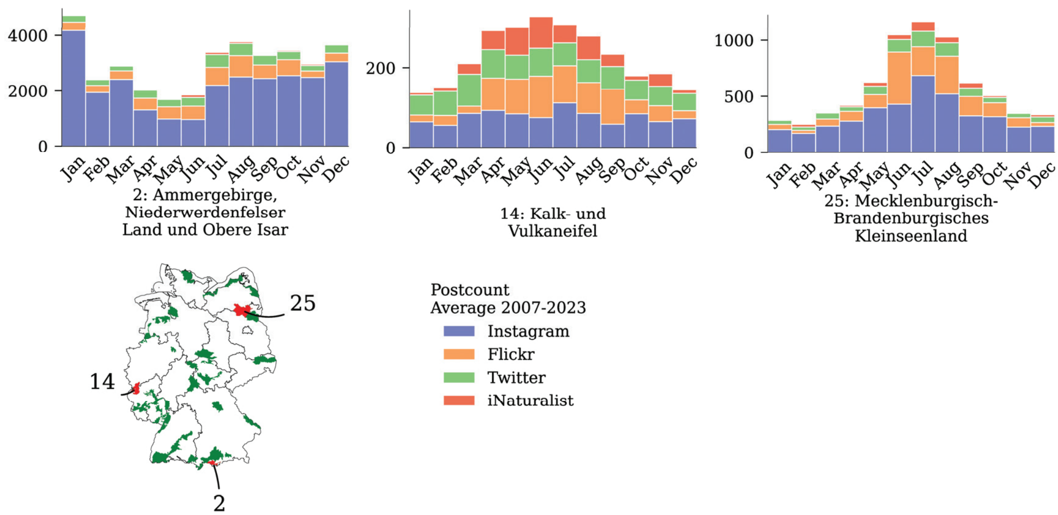

Figure 5. Average monthly number of communication frequency for three of 30 biodiversity hotspots in Germany, measured by intersecting georeferenced posts from four platforms (2007–2022) with hotspot shapes. See Appendix A, Figure A3 for the complete set of visualizations.

4.5. Red Kites (iNaturalist)

Finally, in addition to seasonal patterns, we wanted to explore whether we could identify long-term temporal trends for a selected landscape resource. In this last case study, we filtered for observations of the Red Kite, a relatively common bird of prey in Europe, as an ecological theme (E). After excluding Flickr due to low volume and noisy data, we selected the iNaturalist platform for data collection. Unlike the other data sources explored so far, iNaturalist can be considered as explicit Volunteered Geographic Information (VGI). Explicit VGI directs user behavior toward a common goal for data collection, such as to "Explore and share [. . .] observations from the natural world".[2] The platform is specifically tailored for nature and plant observers, allowing (for example) sharing and filtering by taxonomic species name. From a data collection perspective, this type of sampling is less error-prone and does not require significant data cleaning (see [43]). The map in Figure 6 visualizes all locations from which users sighted and reported Red Kites in Europe between 2007 and 2022. Shown in the background is the shape of the Red Kite range, which is an additional dataset maintained by iNaturalist. The area is derived from user activity and illustrates the possible presence range of the Red Kite.

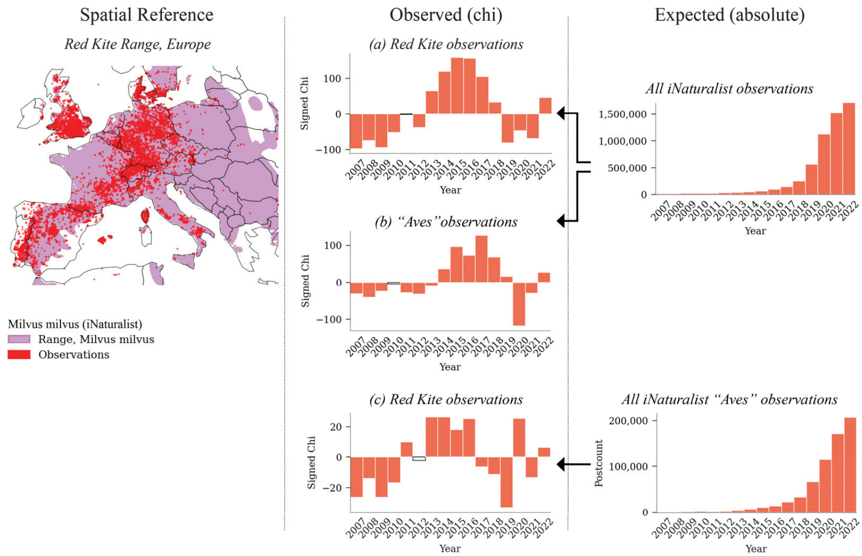

Figure 6. Using umbrella communities, such as all "bird photographers" (Aves), to compensate for within-community variation: (**a**) signed chi for "Red Kite" calculated without compensation, based on all iNaturalist observations, (**b**) test for "Aves" vs. all iNaturalist observations, producing a similar distribution as (**a**), and (**c**) "Red Kite" vs. "Aves" observations to compensate for within-community variation.

Disentangling social (S), ecological (E), and technological (T) couplings in the temporal patterns of these data proves difficult for two reasons. First, the popularity of iNaturalist increased significantly over the observation period (Figure 6). This means that the number of Red Kite sightings must be adjusted to account for the overall increase in observers on the platform. This requires downloading the complete iNaturalist data for all species observations. We used the chi-square equation to account for this effect (see Materials and Methods). Second, due to the concrete filtering, akin to a needle in a haystack, any noise, co-occurring event, or underlying data problem can produce effects that make the results difficult to interpret. The resulting graph (Figure 6a) shows an overrepresentation of Red Kite observations in the years 2013 to 2017. Is this overrepresentation associated with an actual increase in abundance (an ecological coupling) for this particular species? In fact, structured survey data [44] suggest a continuous increase in Red Kite abundance over the last decade.

We questioned this initial assumption. Given that the platform has grown significantly, a bias introduced by certain subgroups, such as birdwatchers, overly joining in some years could also explain fluctuations in Red Kite observations. To test the data based on this hypothesis, the expected frequencies (all iNaturalist observations) can be compared to all observations of the Aves (birds) "umbrella class". The resulting graph (Figure 6b) produces a similar overrepresentation as is visible in Figure 6a, which supports our earlier expectation. Bird photographers joining comparatively early may have led to an overrepresentation of Aves observations shared on the platform during these years. Later, as iNaturalist grew in popularity, the platform also perhaps attracted more species observers from other interest groups, such as plant photographers.

Based on these assumptions, we adjusted for the overrepresentation of Aves photographers by selecting all observations of the class Aves as expected frequencies and calculating chi for the observed frequencies of the Red Kite (Figure 6c). In other words, we examine the overrepresentation of selected subgroups by comparing behavioral similarities to a broader "umbrella" group. While the resulting graph (Figure 6b) still shows an overall increase in relative Red Kite sightings, it is less pronounced than without compensation (Figure 6a). A significant outlier of under-represented Red Kite observations compared to all Aves observations is visible in 2019 (Figure 6c), corresponding to a decrease in general bird photography in the following year of 2020 (Figure 6b). Further investigation of the contributions of the Aves community compared to other subsamples would be necessary to explain this outlier. At the same time, increased filtering also reduces reliability and representativeness. For iNaturalist, representativity is already severely limited because of the required expertise in a selected, specific topic (species monitoring). This may prevent further zooming in on particular regions of interest and limit analysis to small-scale or regional contexts where sufficient data are available.

5. Conclusions

Many of the relationships between visual perception, photo-based communication, and collective social behavior have been known since Urry wrote about "the tourist gaze" [33]. Since then, geosocial media and online communication have radically altered their technological counterparts. Geosocial media and algorithms now influence, distort, and modify the way people perceive their environment. This has given rise to new phenomena, such as mass invasions or cyber cascades, which cannot be explained without considering the global spread of information. Trends such as fake news [45], social bubbles [46], and GenAI are creating an "era of artificial illusions" [47], in which the senses are increasingly challenged to distinguish between the real and the imagined. On the other hand, masses of data on how people perceive their environment are readily available online as what we call opportunistic occurrence data. Assessing perceived landscape change from this data requires disentangling multiple superimposed patterns in the data. For biodiversity and species monitoring, ref. [15] refer to this process as "reverse engineering survey structure" (p. 1226). While their goal is to identify changes in the physical world (species trends) based on data collected online, landscape perception analysis requires equal consideration of the human observer and the physical landscape. Both poles are important subjects of analysis. In this paper, we introduce technology as a third pole. Based on the SETS framework, we distinguish three main domains in which change can occur: the ecological (E), social (S), and technological (T) domains. We discuss the application of the SETS framework in five case studies and show how couplings between these domains can be used to disentangle relationships. Three main findings can be summarized: first, the importance of integrating data from multiple data sources, which refers to the category of aggregation approaches proposed in ref. [15]; second, the consideration of platform biases when filtering user-generated content collected online for specific purposes; third, the existence of biases introduced by the use of technology as a data collection interface. These distortions lead to specific analytical challenges in assessing original landscape experiences and affect planners' agency in decision-making.

In terms of scenic resource assessment, the five case studies can be grouped based on how they address two common tasks: (1) identifying temporal characteristics for a given area or region (national parks 4.2, biodiversity hotspots 4.4), and (2) characterizing and identifying temporal trends for selected scenic resources or phenomena (mass invasions 4.1, cherry blossoms 4.3, red kites 4.5). Generic queries and the integration of multiple data sources can reduce bias and increase representativeness, which helps to gain confidence in the data. In particular, comparisons between data from different platforms help to better understand tourist flows for different user groups. However, only unspecific and broad interpretations are possible, such as identifying and confirming common, recurring seasonal visitation patterns for selected areas and regions. Our results show this for two case studies of US national parks and for 30 biodiversity hotspots in Germany. On the other hand, it proved difficult to identify trends for selected themes or scenic resources. Our observations indicate that overall platform changes (e.g., popularity) or changes in subcommunities (e.g., bird photographers or the group of "red kite photographers" on Flickr and iNaturalist) have a stronger influence on the observed patterns than phenomenal changes, such as the actual growth of the red kite population. A solution for landscape change monitoring could be to first consider observations from umbrella communities, such as all "bird photographers" on iNaturalist (Section 4.5), as the expected value in the signed chi equation. This generic query can then be used to compensate for within-community variation to visualize corrected trends for specific observations (e.g., to normalize observations of specific bird species). As an exception, observations of cherry blossom, as a globally perceived ecological event, are found to be very stable and seem to be less affected by changes in communities or technology. One possible interpretation is that the phenomenon is valued equally across many cultures and communities. Such events may therefore be useful as "benchmark events" to compensate for within-community variation in the study of more localized aspects of landscape change.

Our results show that platform biases exist toward individual poles that affect their suitability for assessing some contexts of landscape change better than others. iNaturalist or Flickr, for example, features metadata that appears more directly linked to the actual perceived environment. This makes these platforms better suited for filtering data related to actual ecological change (E), such as the timing of events like flowers, fruits, and leaf color change. Other aspects related to broader societal behavior, human preferences, and collective spatiotemporal travel footprints (S) may require consideration of a broader set of platforms, including (e.g.) Instagram or Twitter. Due to the rules and incentives on these platforms, not all aspects are captured equally. In our study, we observed that charged discussions with positive and negative reaction sentiments, associations, metaphors, and political couplings are primarily found on X (formerly Twitter) and Reddit. The influence of technology and algorithms also varies, as shown in our case studies and confirmed by other authors [36]. Capturing these different perspectives and conditions of opportunistic data contribution helps planners gain a more holistic understanding of the dynamics influencing visual perception and behavior observed in the field. Cross-platform comparisons, such as in Section 4.4, are found to be particularly useful in reducing bias and providing actionable knowledge for decision-making. The results can be used, for example, to increase environmental justice or reduce socio-spatial inequality [24]. It can also help develop techniques to counteract phenomena associated with the technological domain, such as crowd bias toward certain visual stimuli and amplifying imitative photo behavior.

When evaluating scenic resources through the "lens" of user-generated content from geosocial media, we recommend that planners consider the following three analytical challenges. First (1), some ecological features (E) may be valuable even if they are not perceived by someone. This applies to ecological phenomena that are rare, take a long time to occur, or cannot be recreated or replaced once lost. Such features may be difficult to detect in user-generated content and with quantitative analysis due to the selective focus and bias of crowd perception [28]. Second (2), some content may be shared online for social purposes (S) even if the original experience was not perceived as scenic or valuable. We observed this effect for places affected by "mass invasions" (Section 4.1). Here, users appear to selectively share photos that show few people in solitary scenes from what are actually crowded vantage points. Tautenhahn explains this phenomenon as "self-staging" in the landscape [32] (p. 9). Finally (3), even in those cases where people do share their original experiences with, e.g., photographs of crowded scenes, geosocial media ranking algorithms (T) may prevent these experiences from ever gaining a wider user "reach" by, e.g., downgrading unaesthetic or negatively perceived content. These algorithmic effects can make it difficult for planners to interrupt feedback loops, such as mass invasions, with negative consequences for infrastructure, ecology, and human well-being (see [4]). In the fields of landscape and urban planning, the shown analyses over time can help to better understand these unique transient characteristics of places, areas, and landscapes, to protect and develop specific ephemeral scenic values, or to propose actions to change negative influences.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/land13071091/s1, S1 (HTML File): 01_mass_invasion.html, S2 (HTML File): 02_reddit_api.html, S3 (HTML File): 03_reddit_pmaw.html, S4 (HTML File): 04_reddit_privacy.html, S5 (HTML File): 05_reddit_vis.html, S6 (HTML File): 06_cherry_blossoms.html, S7 (HTML File): 07_hotspots.html, S8 (HTML File): 08_milvus_conversion.html, S9 (HTML File): 09_milvus_maps.html, S10 (HTML File): 10_milvus_chi.html. Note: Only HTML conversions are attached to this paper. The notebook files (ipynb format) and data are made available in a separate data repository [31].

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Data Availability Statement: All data used to produce figures and results in this work (see code Supporting information S1–S10) are made available in a public data repository https://doi.org/10.25532/OPARA-572.

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Appendix A

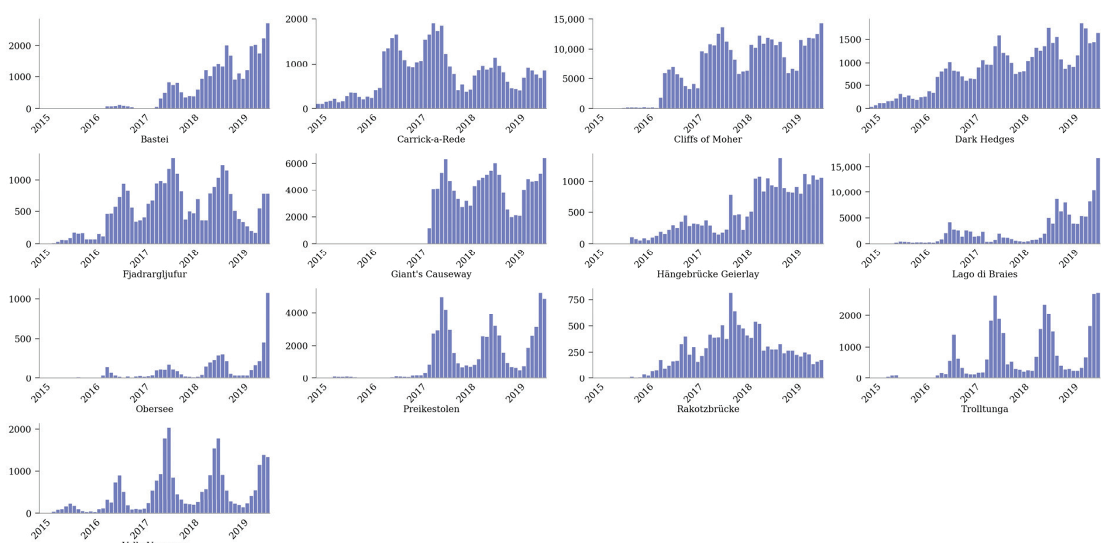

Figure A1. Time series visualization of communication volume (Instagram) for all 13 assessed vantage points in Europe that are known to have shown "Mass invasions".

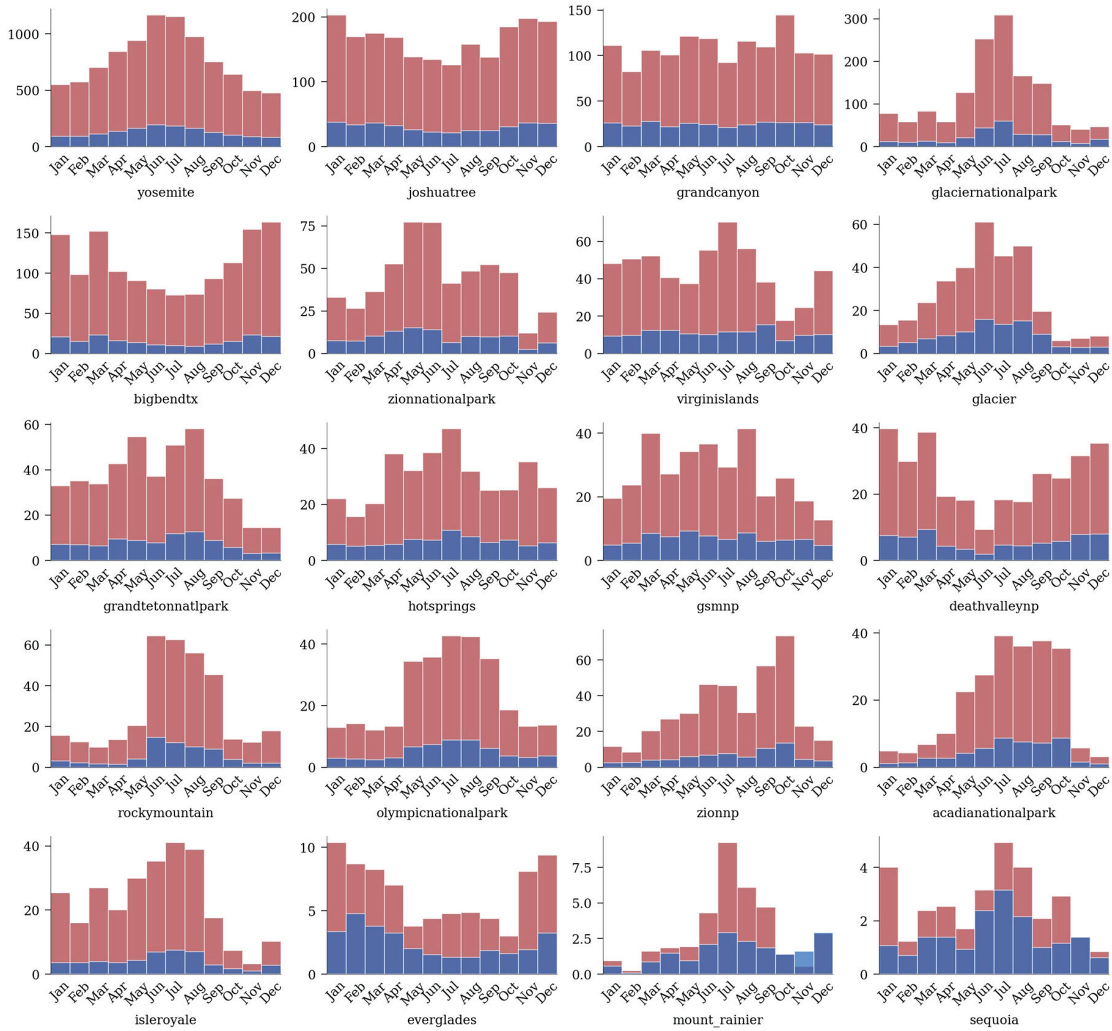

Figure A2. Barplot visualization showing seasonal communication volume for all assessed national parks based on comment (red) and post (blue) count from subreddits.

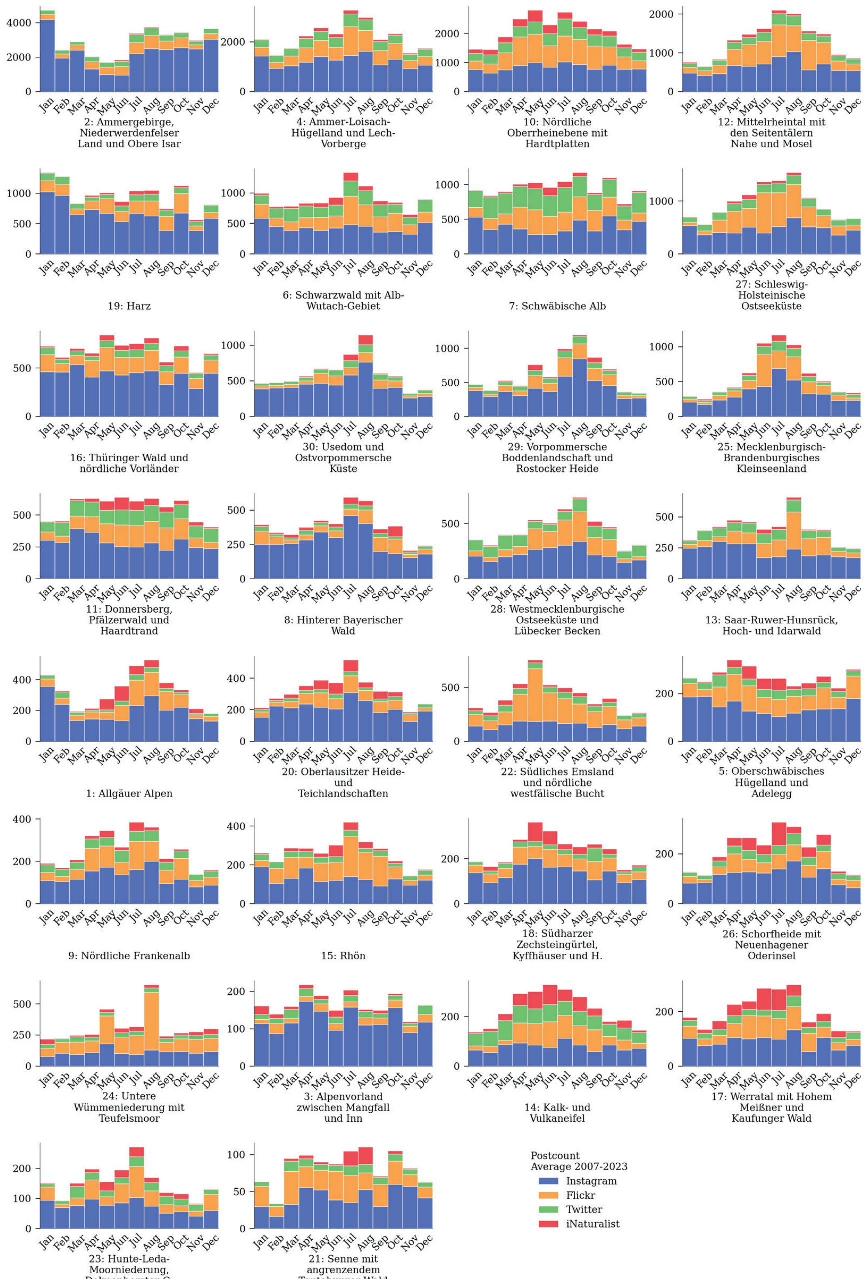

Figure A3. Average monthly number of communication frequency for 4 social media platforms and for all 30 biodiversity hotspots assessed in Germany.

Notes

1 Available online: https://lbsn.vgiscience.org/ (accessed on 18 July 2024).

2 Available online: https://www.inaturalist.org/ (accessed on 18 July 2024).

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Systematic Review

How Highway Landscape Visual Qualities Are Being Studied: A Systematic Literature Review

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Abstract: Highways play a vital role in the road transport system, connecting regions and cities in many parts of the world. It may sometimes offer scenic views or a visually appealing environment based on the availability of unique compositions of natural and man-made elements within the highway vicinity. The highway's landscapes could significantly impact the journey experience; thus, it is essential to emphasize the need to preserve a visually appealing, safe, and enjoyable highway environment. Although many studies have been conducted regarding the highway visual environment, currently, there is a lack of comprehensive understanding of perception variables that could affect viewers' preference for highway landscapes. Therefore, this study aims to understand the background of the highway landscape and identify the perception variables and their effect on the preference for highway landscapes. This study conducted a systematic review by searching for keywords in three databases: Web of Science, Scopus, and Google Scholar. The review included 37 research articles published between 1993 and 2023 that met the criteria. An additional nine relevant papers were included through a 'snowballing' approach to supplement the research and results. The results of the study focused on multiple perspectives of highway landscape views, viewers' perspectives and the diversity of highway landscape purposes, viewers' preferences for highway landscapes, the approach to preferences, and related key variables. This background knowledge deepens the understanding of visual preferences for highway landscapes and helps refine the selection of perceptual variables, establishing an essential reference criterion for professionals.

Keywords: visual preference; highway landscape; highway landscape preference; highway landscape preference assessment; perception variable

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1. Introduction

Highways serve as a crucial component of the road transport system, connecting various cities, towns, and regions with networks of linkages [1]. While primarily serving the purpose of transportation, highways may also offer viewers the chance to witness impressive scenery, which adds to the enjoyment of the journey [2]. Thus, the highway landscape refers to the road's visual environment, integrating natural and cultural landscapes to create a comprehensive visual journey [3]. In other words, the highway landscape comprises diverse landscapes that viewers (including users of the highway and others who look at it in different ways) may encounter along the highway. These unique landscapes, typically characterized by the natural landscape of undulating terrain, rich flora, fauna, and water resources, or the cultural landscape of man-made elements [4], enhance the driving experience and provide opportunities for cultural appreciation and natural awareness.

In addition, highway landscapes are not just physical components but key contributors to the overall highway landscape aesthetics, offering valuable insights for aesthetic analysis [5]. Highway landscapes also highlight that local culture should be preserved and evolving, adding intrinsic character and diversity to regional cultural identity [3,6]. This cultural aspect is pivotal in influencing visual preference and affects how viewers perceive and appreciate the scenery along their journey [2,7]. Therefore, these insights are invaluable to experts responsible for maintaining the visual integrity of highway designs and the surrounding landscapes.

1.1. Highway Development and Landscape Impact

Urbanization has dramatically transformed traditional rural landscapes into urban settings in recent years, fundamentally altering land use and arrangement [8]. This transformation is reflected in the changing landscape observed by highway viewers, with structures intruding into otherwise rural areas with increasing frequency [9]. As urban areas expand, the need for mass transit, including constructing and expanding roads and highways, is undeniably essential [1]. However, their construction often negatively impacts the natural surroundings, especially regarding land coverage and ecosystem improvement [10]. This trend leads to urban sprawl's cluttered, unattractive, and monotonous landscapes. Unfortunately, many highways have been constructed without adequate consideration of visual preference or quality, leading to the degradation of valuable visual landscapes [1]. Thus, highways fulfill transportation purposes and serve as markers of landscape quality changes, directly influencing viewers' perceptions and experiences of these transformations.

Meanwhile, the highway, as a medium for the combination of the natural landscape and man-made structures, emphasizes the importance of landscape design and environmental regeneration [11]. It also reflects that the combination of natural and man-made elements of the highway symbolizes the harmony between highway engineering and environmental management. However, highway development frequently undermines valuable natural and historical landscapes, leading to the loss of precious areas [12]. The construction of a major highway can profoundly alter a region's landscape ecology and scenic beauty [6]. The highway infrastructure has contributed significantly to environmental change, manifesting in alterations in land use, the loss of green areas, and changing views of and from roads [12]. Additionally, the aesthetic characteristics of minor infrastructures and vegetation alongside highways critically influence the perceived landscape quality of the roadway [6]. Hence, assessing visual preference becomes crucial when considering both the impact on the views from the highway and the aesthetic implications of the highway itself on the surrounding landscape. This consideration underscores the complex relationship between visual landscape quality and road developments [13].

1.2. Visual Preference on Highway Landscapes

The concept of "visual preference" can be interpreted as a psychological assessment of the observed human interaction with the environment [5,14]. This paradigm posits that individuals evaluate and react to their surroundings through emotional responses [15]. In this context of high-speed movement, the experience of driving at high speeds narrows the viewer's field of vision, primarily focusing on the immediate foreground landscape, tending to fade away, while attention is more consistently directed toward distant views [8]. In other words, highway landscapes are linear and impose limitations on viewers' appreciation in terms of visual perspective, distance, and landscape identification. Therefore, this focus shifts towards the dynamic interaction between road viewers and the scenery outside their windows while traveling at high speeds [7]. A journey becomes exhilarating for viewers when the highway presents highly preferred scenic vistas, incorporating unique landscape elements [3]. This encompasses the impact of roadside landscaping on road viewers' experiences, including their ability to navigate, control, and enjoy their journeys [5]. Hence, it is imperative for highway landscapes to provide road viewers with, or allow them to have, a comfortable, pleasant, safe, and visually appealing environment for their relaxation.

Yet, in recent years, people's preferences and perceptions of landscapes have been impacted significantly due to rapid urbanization [16]. The integration of the highway with its adjacent landscape has significantly altered how the quality of the landscape is perceived [6]. Despite the extensive discussions on visual preferences in highway landscapes, a gap remains in the presence of unified and comprehensive perception variables for evaluating these preferences, especially in the context of the environmental impacts of urbanization and highway development. In order to address this gap, this study was dedicated to a systematic review of the existing literature on visual preference assessment in highway landscapes. Our aim is to synthesize information and identify the perception variables for evaluating highway landscape preferences. The purpose of identifying these perception variables is to deepen the understanding and perception of highway landscapes' visual preferences, aid in preserving cultural and natural values, and meet the needs of a changing society in the context of urban sprawl.

2. Materials and Methods

2.1. Keyword Selection

The keyword selection for this systematic review could be divided into four main themes: preference, visual, highway, and landscape. Keywords such as "preference" and "perception" have been included within the domain of preference. Landscape preferences are a combination of the environment's biophysical characteristics and human perceptions [17]. Perception plays a key role by providing sensory input and an initial interpretation of the environment [18], while preferences represent an individual's preferences and choices based on that interpretation [19]. In the field of landscape studies, research on visual perception investigates the fundamental concept of beauty, exploring aspects such as goodness, attractiveness, and preference. The interplay between perception and preference is complex, as each influences and shapes the other in a constant feedback loop. Hence, the review also added "perception" as a key term.

The terms "visual", "scenic", and "aesthetic" cover a broad range of visual experiences and attributes linked to personal preferences and perceptions [20]. "Visual" refers to any observable element, while "scenic" focuses on the beauty of natural landscapes. "Aesthetics" involves a deeper artistic and philosophical interpretation of beauty [21]. These terms were selected to facilitate the analysis of how individuals perceive and evaluate landscapes' visual aspects of landscape, including natural and man-made features. Furthermore, incorporating terms like "road", "roadway", or "street", in addition to "highway", would broaden the scope to enrich various road environments and their impact on visual preferences. This comprehensive approach is based on recognizing the linear character of the road landscape, which significantly affects the visual experience and shapes landscape composition [10,12]. Finally, the systematic review's keywords are summarized as follows: "preference" OR "perception" AND "visual" OR "scenic" OR "aesthetic" AND "highway" OR "roadway" OR "road" OR "street" AND "landscape".

2.2. Relevant Literature Screening

The methodology used to screen the relevant literature for this study was based on a keyword search and followed the guidelines of a systematic review (Figure 1). Initially, three databases—Web of Science, Scopus, and Google Scholar—were chosen to screen the literature preliminarily. Articles meeting the following criteria were selected for inclusion in this study: (1) publication between 2013 and 2023; (2) publication in an English scientific journal; and (3) classified as research papers, review papers, or conference papers. After screening and examining papers based on the given criteria, 35 out of 546 papers finally met the final requirements. To supplement this limited number, "snowballing" was employed by reviewing the reference lists and citations of the selected papers and adding six relevant papers. Although these additional papers were published earlier than 2013, they are highly pertinent to this review. Finally, 37 papers were ultimately selected—28 research papers, 1 book chapter, 2 review papers, and 6 conference papers published between 1993 and 2023.

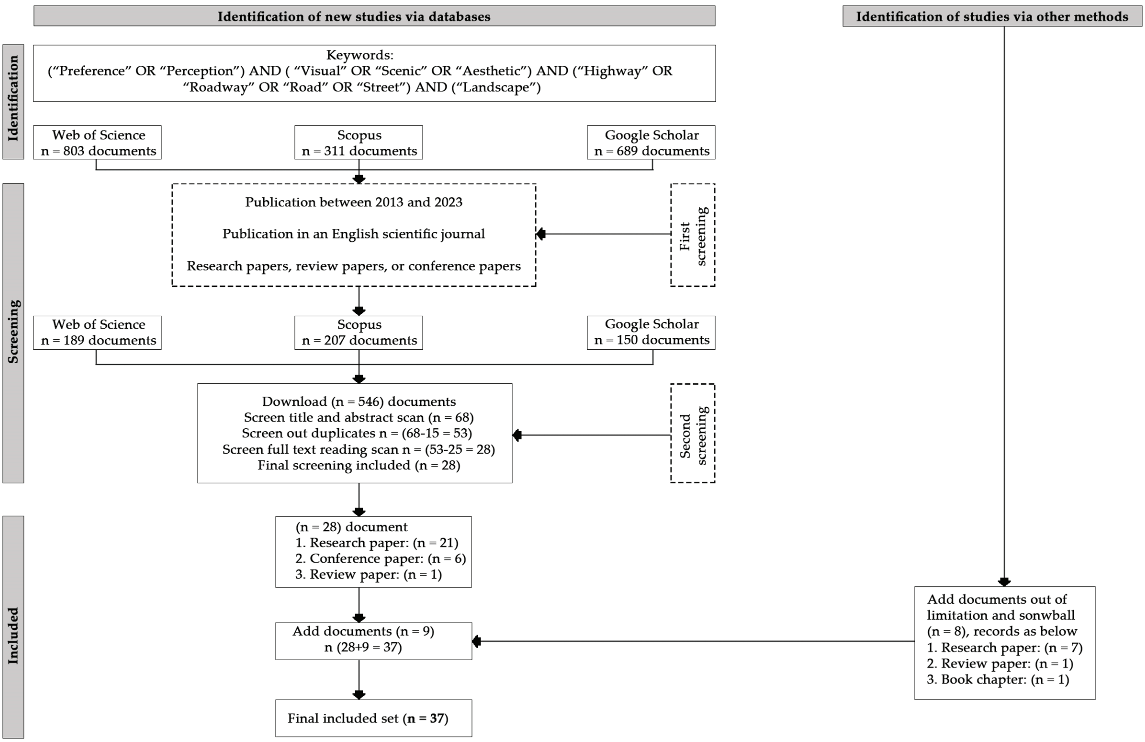

Figure 1. Flowchart describing the literature-screening process for systematic search reviews.

2.3. Data Collection

For this study, a thorough analysis and reading were conducted on the selected articles, and the related information was gathered and organized in an Excel spreadsheet. The recorded information consists of several elements, such as the types of roads, the landscape character in which the road is embedded, the types of viewers, the assessment methods, the response format, the media used to represent the view, and the criteria or variables used in the assessment. Appendix A, Table A1 presents a comprehensive overview of the collected data.

2.4. Data Analysis

This study presents the synthesis of the information referred to in Appendix A of Table A1, with the objective of strengthening the connections between the literature and enhancing the depth of the findings. Initially, it explored the interactions between highways and their surrounding landscapes from multiple perspectives by integrating the various types of roads with the landscapes in which they are located. Secondly, it considered the interaction between the viewer's perspective and the research purposes across different roadway contexts. Next, an in-depth understanding and detailed analysis of viewers' preferences in highway landscapes were provided. Additionally, in order to achieve a comprehensive understanding of the research methodology, the evaluation techniques, response formats, and the media used to present the views were examined. The discussion of evaluation criteria or variables was intended to identify unified and comprehensive perception variables for assessing highway landscapes.

3. Results

In order to better understand the assessment of perceptual variables on highway landscapes, it is essential to have a clear knowledge of the contextual aspects of highway landscapes (discussed in Section 2.4). The results of the study are, therefore, divided into the following categories, which are discussed in the following sections:

- Intersecting landscapes and a multidimensional exploration of highway landscapes;
- Understanding perception and preference in the visual dynamic of roadside landscapes;
- Understanding a viewer's preference in highway and roadside landscapes;
- Assessing highway landscape visual preferences through various approaches;
- Identifying key perception variables in assessing the visual preference of highway landscapes.

3.1. Intersecting Landscapes and Multidimensional Exploration of Highway Landscapes

Highway landscapes are the main focus of this study; however, adding different types of roadway landscapes broadens the area and enhances meaningfulness with respect to understanding more in-depth views of highway landscapes. The highway exhibits diverse landscapes, including natural landscapes [2–5,8,10,12,22–26], such as mountains, forests, water features, and roadside vegetation. Meanwhile, cultural landscape elements within these highway landscapes serve an integral purpose. For instance, the historic structures within the view angle of a highway enhance the architectural characteristics of the highway and maintain a relationship with viewers, linking them to the heritage of a region [2,25]. Furthermore, the topographical variations further add visual interest as highways traverse varied landscapes, from mountainous landscapes with high peaks and ridges, to basins, enhancing the highway travel experience [4,25]. At the same time, such scenes are also depicted on scenic routes, as explored in studies [27,28], which highlight valleys, vegetation, water features, stone walls, pastures, historic residences, a blend of natural and pastoral scenes, forested areas, and open vistas. This demonstrates the richness and diversity of what the highway can do as a tourist roadway.

When highway landscapes pass through rural or urban areas, they provide another multifaceted perspective. For example, the highways traversing rural areas reveal landscapes dominated by agricultural lands and small towns [3,5,10,13,29], offering a glimpse into the serene rural life seen on rural roads [30,31]. The experience is different, however, as the leisurely pace of rural roads allows for a more relaxed appreciation of the scenery. In contrast, urban highways pass through transition zones that are distinct from the bustling commercial, residential, and green spaces of urban streets [32–36].

Studies [5,9] demonstrate how highways can combine these two landscapes, mirroring the rural–urban fringes discussed in [37], displaying characteristics of an integrated landscape. Notably, certain regions along highways display distinct landscapes, such as palm oil estates [3] and volcanic landscapes [12], adding depth to the visual narrative for viewers. Therefore, highway landscapes represent a dynamic interplay of natural beauty, historical richness, and the built environment. The variety of landscapes emphasizes the highway's role as a connecting link between destinations, different environments, and cultural experiences.

3.2. Understanding Perception and Preference in the Visual Dynamic of Roadside Landscapes

The visual quality of human surroundings, especially within highways, urban streets, and rural roads, profoundly impacts daily experiences, comfort, and satisfaction. To this end, numerous studies have explored the perceptions and preferences of people affected by these landscapes—such as drivers, passengers, and pedestrians, as illustrated in Table 1. For instance, studies focusing on highway landscapes have primarily assessed the visual quality experience and preferences of the public [5,8,9,24] or highway users [3], emphasizing the recognition of the importance of their perceptions. Similarly, studies involving pedestrians [32] or residents [36] have further aimed to evaluate the aesthetic aspects of specific streets or roads in urban settings. Notably, a study on urban roads has investigated how the presence of poplar trees enhances the aesthetics of urban road landscapes, as perceived by 35 university faculty members [33].

In rural settings, studies [30,31] have evaluated the visual quality of rural roadside landscapes and focused on understanding public or specific group preferences for various rural landscapes. For mixed urban and rural areas, as seen in [37], the aim is to explore residents' preferences for agricultural and development patterns along urban and rural roads through residents, with the simultaneous intention of promoting economic development and improving the visual quality of the roadside. Scenic roads have also been analyzed for how different landscape components contribute to visual quality, comparing residents' preferences for natural, cultural, and mixed landscapes [24]. Moreover, study [28] has focused on the aesthetic characteristics that contribute to the success of scenic road design, examining motorists' perceptions. Therefore, those studies emphasize the importance of understanding the perceptions and preferences of different groups of people towards these landscapes.

The exploration of landscape preference extends beyond visual quality, incorporating the interplay between sensory experiences and environmental perception. Specifically, with regard to studies targeting specific demographics, such as university students aged 18 to 27 [29] and online social media users aged 18 to 47 [13], these studies have explored the interactions between traffic noise and highway visual perception, intending to help us understand how traffic noise affects people's visual perception of highways. Moreover, a comparative analysis between expert opinions and the general public's views further illuminates the significance of comprehensively adopting diverse approaches to understanding and assessing scenic beauty in highway landscapes [2,6,7,10]. However, studies [35,38] have mentioned testing new methods' effectiveness through comparison. Therefore, such a comparison provides a more profound comprehension of landscape aesthetics in highway landscapes and encourages the innovation of new approaches.

Studies lacking direct participant (only expert) involvement in highway landscapes [4,9,11,12,22,23,25,26,39] have aimed at creating a new approach for evaluating and improving landscapes around highways, emphasizing aesthetics, environment, and safety. Similarly, the urban-centered study employs innovative techniques such as deep learning [40] and other machine-learning approaches [34]. On the other hand, study [41] has summarized the visual characteristics to improve the understanding and assessment of urban landscapes' visual quality and perception.

Overall, these studies affirm that all respondents, considered as viewers of the roadside landscape, play a pivotal role in defining research directions. Perspectives and experiences from different groups, such as drivers, passengers, and specific age demographics, provide unique ideas for understanding and evaluating roadside landscapes' visual and environmental quality. These studies not only reveal the viewer's visual preferences for highways and urban streetscapes, but also highlight the need to incorporate diverse perspectives into the evaluation process.

Table 1. Show the differences between viewers and purposes.

Type of Roads	Viewers	Purposes	References
Highway	Highway users or the general public	Assessing experiences and preferences regarding highway landscapes' visual quality.	[3,5,8,9,24]
	College students (18–27), users online (18–47)	Examining how traffic noise impacts visual perception of highways.	[13,29]
	Experts and the general public	Adopting diverse approaches in assessing scenic beauty.	[2,6,7,10]
	None	Exploring new methods for highway landscape evaluation.	[4,9,11,12,22,23,25,26,39]

Table 1. *Cont.*

Type of Roads	Viewers	Purposes	References
Urban street	Pedestrians, residents	Assessing the visual quality of specific streets or roads.	[32,36]
	Academic staff	Understanding how poplar plantings affect people's visual preferences and perception of landscape quality.	[33]
	Experts and the general public	Exploring new methods for people's perceptions of the urban road landscape.	[35]
	None		[34,40,41]
Scenic road	Residents	Assessing the significance of natural and cultural features in landscape preferences.	[24]
	Motorists	Exploring how the design of the road influences motorists' perceptions and emotional responses.	[28]
	Experts and the general public	Exploring new methods for enhancing the driving experience.	[38]
Rural road	Public, motorcyclists	Assessing the visual quality of the road landscape.	[30,31]
Urban–rural road	Local residents	Understanding resident preferences for agriculture and development along mixed urban and rural roads.	[37]

3.3. Understanding Viewer's Preference in Highway and Roadside Landscape

Regarding scenic road selections, the public's judgment is influenced by various factors, demonstrating strong personal preferences throughout the decision-making process [38]. In most cases, such strong expressions of individual preferences can lead to a consensus, revealing the public's widespread appreciation or aversion towards specific types of landscapes. In highway landscapes, viewers strongly prefer natural elements such as farmland, limestone hills, mountains, and other natural characteristics [3], as well as distinctive bodies of water and building features [2]. These results are also found in scenic roads [27], confirming an appreciation for natural aspects such as water and vegetation and highlighting the value of cultural elements in their role in preferences, such as stone walls and historic residences. Conversely, cultural landscape elements like towns, residential, and industrial areas have low visual appeal [2,3], perhaps due to inadequate environmental integration or insufficient maintenance. Such results appear consistent with rural road landscapes, landscapes with roadside settlements, and commercial structures, which are less attractive [30].

The composition of roadside vegetation also significantly impacts visual preferences. Viewers tend to prefer diverse and colorful vegetation types [5] over a uniform mix of plant species [24]. Scenic road design elements, such as reverse curves and the strategic use of color and texture in plantings, significantly contribute to the positive aesthetic experiences of viewers [28]. The preferred combination of vegetation types consists of trees in the background, followed by shrubs in the middle, and grass and flowering plants in the foreground [5,24]. This preference extends to rural roads, where landscapes with water bodies in the foreground and wooded backgrounds are particularly valued [31]. Some studies [9,33,37] have also provided additional evidence of the role of trees in enhancing the visual quality of roads, emphasizing their indispensable contribution to roadside aesthetics.

However, roadside trees and shrubs can negatively impact sightlines on major roads [42], and neglected vegetation maintenance can deteriorate visual experiences on rural roads [30]. These findings highlight the importance of balanced ecological management to maintain both aesthetic appeal and safety. Particularly, study [7] has also emphasized that the openness of the field of view is crucial in enhancing the viewer's aesthetic preference in a dynamic environment. Interestingly, there is a discrepancy between the results obtained from the static questionnaire survey and the dynamic simulation of the highway landscape.

While water bodies are usually seen as enhancing preference, their appeal diminishes in dynamic assessments, suggesting that motion could influence landscape perception [7]. Similarly, cultural elements usually considered negative, such as bridges, are perceived positively in dynamic contexts.

Furthermore, both frequency and noise levels affect visual preferences on the highway. According to study [5], infrequent viewers express higher satisfaction with the type and layout of roadside vegetation, while frequent highway users prefer a wider variety of colorful vegetation. Elevated traffic noise may affect the visual experience, especially with high traffic volumes [13]. The study indicates this auditory impact heightens the visual disturbance by an average of 11.6 on a scale of 1 to 100 across different scenarios. This effect slightly strengthens at 300 m (compared with 100 or 200 m), indicating a subtle but noticeable enhancement in the interaction between auditory and visual perceptions with increased distance from the noise source.

In summary, highway landscape preferences are influenced by natural and psychological factors, personal experiences, and practical considerations. Various factors, including diversity, continuity, management level, natural feeling, and aesthetics of roadside greening, influence the visual quality of roadside landscapes [36]. With proper management and maintenance, it is possible to create highway landscapes to meet the aesthetic needs of different viewers and enhance the overall experience of road travel.

3.4. Assessing Highway Landscape Visual Preferences through Various Approaches

Through a systematic review of the literature, three main approaches have emerged in exploring methods to assess highway visual preferences, incorporating urban, rural, and scenic road landscapes: the viewer's perception approach, the expert approach, and a hybrid of the two approaches (Figure 2).

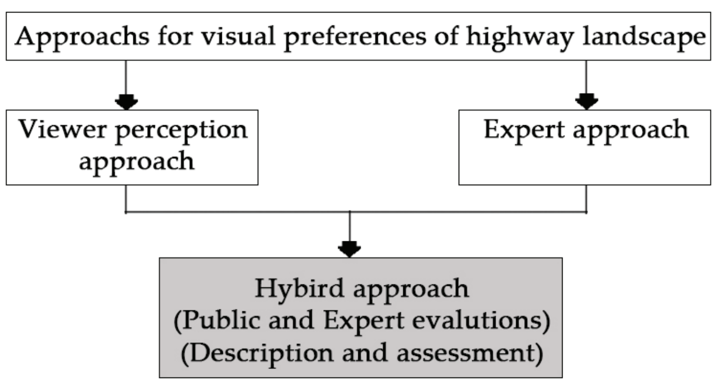

Figure 2. Three different approaches.

3.4.1. Perception Approach

Assessing highway landscapes is a complex process, significantly influenced by its subjective nature, which heavily relies on an individual's perception and response to the landscape [5,24]. Typically, individuals tend to prefer natural landscapes that are easily understandable and have various features; however, preferences for such landscapes can vary widely depending on the viewer's background [31]. This approach relies mainly on quantitative methods involving a specific group or the general public. In a viewer perception approach as applied in landscape studies, mean ratings are utilized to evaluate individual perceptions of highway landscapes. Therefore, the reliability of the results may be higher when using this approach than relying solely on experts [20].

The perception approach in assessments generally includes surveys and the evaluation of photographs selected by researchers, which participants are asked to rate. However, assessing how image quality influences viewer ratings introduces a challenge, as it may introduce bias through the researcher's selection of landscape images [8]. To address this concern, study [8] has proposed conducting individual photographic surveys using disposable cameras, enabling participants to capture landscapes they cherish and, thus, avoid the bias that might arise from pre-selected images. To closely mimic realism further, some studies, including [13,29], have adopted computer visualization techniques and edited audio recordings to simulate highway scenarios in a laboratory setting. This approach is intended to enrich the study's context and potentially increase the interpretability of the findings related to visual and auditory perceptions of the landscape. Overall, this approach based on perception provides a quantifiable and reliable way to produce accurate results. It comprehensively explains viewers' perceptions of the scenic beauty of the highway [24] and understands the vital influence of the biophysical environment along the road. However, it faces challenges such as the longer time required for collecting surveys and handling the data.

3.4.2. Expert Approach

The expert approach favors an objective methodology that converts the physical characteristics of the landscape into critical indicators that influence visual quality [20]. Grounded in the experience and judgment of experts, this approach involves a systematic assessment and recommendations process on landscape characterization regarding established norms and standards [20]. Experts typically elaborate and explain features of the highway landscape, then evaluate them according to the relevant criteria [10]. This approach represents a cost-effective strategy [20] and is widely adopted [27], efficiently achieving relevant objectives. However, it does face some remaining shortcomings. This approach primarily relies on experts' opinions, and the variables used by the experts are not revealed to be good predictors of preference [2,10]. Experts are also assumed to be broadly consistent in their landscape assessments while overlooking the viewer's subjective perception [2]. Such limitations may affect the accuracy and reliability of the results. While studies [34,40] have applied deep-learning models to innovate public assessment systems and examine urban landscape perceptions, these do not inherently assure the validity of the variables used in these models.

Moreover, the expert-centric approach somehow fosters investigating and implementing new assessment approaches. For example, study [11] has incorporated expert analysis with a holistic methodology that synthesizes quantitative and qualitative methods, including set-pair analysis, to systematically evaluate the highway landscape's quality through a structured blend of various criteria and indicators. Study [25] has focused on the impacts of visibility and landscape management, using a GIS-based viewshed analysis and visual magnitude analyses to carry out a visibility analysis, providing unique information about the topography visible from the highway. Study [26] has combined expert analysis with data extraction methods using Google Maps and Google Earth for landscape elements, including evaluating the visibility and prominence of landscape features along road segments. Generally speaking, the expert-centric approach often results in the adoption of newer technologies. However, it is essential to note that these choices are still influenced by the background and experience of these experts, and the outcomes can be somewhat controversial.

3.4.3. Hybrid Approach

Study [20] has mentioned that this hybrid approach could be considered more informative because it facilitates a direct comparison of the two approaches (expert and viewer perception), aiming to understand and resolve their inconsistencies systematically. However, only a few studies in the reviewed literature have adopted this approach. For example, study [35] has integrated expert analysis to develop the indices and viewer perceptions to validate the assessment method. Study [6] has compared the visual highway landscape quality obtained through a systematic photo analysis with the landscape preferences determined using a survey. Similarly, study [10] has investigated how experts use descriptors to evaluate landscape quality and correlate their assessments with the ratings of landscape beauty from untrained observers. Moreover, studies [2,42] have evaluated the quality and differences of scenic spots by combining expert analysis and viewer perception. A notably innovative application of this approach is found in study [38], where the development of the Autobahn system—a tool for generating scenic routes using Google Street View images—is evaluated against traditional route-planning algorithms. These approaches comprehensively compare the results obtained by both approaches. However, study [7] has combined a survey of user perceptions with expert analysis. It has employed experts to quantify visual attractiveness objectively through physiological measurements, which further explains the research results. Additionally, certain studies of the hybrid approach [7,42] have also used restoring real scenes to better understand visual preferences in real moving environments. Generally speaking, it allows for a nuanced evaluation of landscape quality, bridging the gap between objective expert assessments and subjective viewer experiences. This hybrid approach can yield good results but requires more time, energy, and financial resources.

3.5. Identifying Key Perception Variables in Assessing Visual Preference of Highway Landscapes

The landscape visual preference assessment approach has three main assessment variables and criteria: physical, aesthetic, and psychological [6]. The physical variable primarily emphasizes the significance of environmental elements and their interactions, including both natural and cultural elements [30]. The aesthetic descriptor arranges the landscape's physical features into visual components such as shapes, colors, lines, and compositions [5]. In other words, both physical and aesthetic variables are based on the physical characteristics of the landscape. Conversely, psychological variables delve into how the landscape's physical attributes impact viewers' perceptions [32,33], highlighting the importance of these physical and aesthetic features in shaping the viewer's visual perception [6].

In highway landscape assessment, these landscapes rely heavily on physical features to trigger visual and psychological evaluations, thereby playing a pivotal role in the assessment process [7]. Thus, study [2] has suggested that an initial step in highway landscape preference assessment should involve thoroughly categorizing and describing the observed landscape. This is followed by considering variables related to visual perception before proceeding with the assessment.

The initial stage in highway landscape assessment, called highway landscape characterization, involves defining, classifying, and labeling a landscape area's distinctive highway landscape character [43]. This stage requires a detailed description of each area's character, distinguishing it from others based on the diversity, organization, and spatial arrangement of landscape features [30]. This process ultimately gives each area a distinct character that sets it apart from its surroundings [2]. Reviewed studies [27,31] utilize the landscape's physical variable for visual evaluation, highlighting that physical factors can influence the viewer's assessment of landscape elements. However, study [44] has argued that using the landscape's physical attributes as the sole assessment criterion is inadequate. It should be viewed as an objective unit that cannot be used in isolation to explain visual preferences. Additionally, cultural features of the landscape can be considered secondary and potentially negative [27]. Therefore, identifying highway landscape types is a key step in understanding visual preferences [2]. As previously mentioned (discussed in Sections 3.1 and 3.3), highways traverse diverse areas, such as mountains, forests, cities, and villages, and these areas exhibit changes in landscape character and topography. The classification of highway landscapes is influenced by various factors, including land use (such as agricultural, residential, commercial, and industrial), topography (such as mountains, hills, and plains), and land cover (such as vegetation, bodies of water, and man-made structures).

The second stage assesses the features or elements of the highway landscape that are, then, incorporated into appropriate management, planning, and preservation options. The process includes considering variables related to visual perception. Experts and viewers assess these variables to determine the visual preferences of the highway landscape. Therefore, identifying key variables relevant to visual perception becomes critical in this process.

According to study [2], human vision is vital in understanding and exploring the environment and assessing the current situation and possible future changes. The legibility and coherence of the environment facilitate comprehension, while complex and mysterious environments encourage exploration [2]. Similarly, naturalness is an important concern in viewers' understanding and exploration of the environment, with many programs pointing to natural attributes as a central element in viewers' ideals and preference choices [10]. Although the study's results [10] have shown that naturalness does not significantly improve the ability to predict preferences, many studies include naturalness in their evaluation framework. Moreover, visibility (openness) is highlighted as a key criterion for landscape preference, with the literature reviewed consistently emphasizing the impact of openness on preference [2,7]. Objective indicators are used to assess street visual quality intelligence, with greenery and the sky view responding to the openness and closure in the street view [34], which is enough to show the importance of openness. Finally, imageability further enriches this discussion, denoting the distinct characteristics that make an area memorable or easily recognizable [32], facilitating landscape differentiation. Study [34] has indicated a moderate correlation between imageability and visual quality, suggesting that streets with distinct imageability are perceived as having a higher visual quality.

In sum, highway landscape preference assessment primarily revolves around seven variables: naturalness, openness, complexity, coherence, legibility, mystery, and imageability. These variables are organized into three main criteria: highway-landscape visual ambiance (openness and naturalness), highway-landscape visual composition (complexity, coherence, legibility, and mystery), and highway-landscape visual impression (imageability). Therefore, the whole process is displayed in Figure 3.

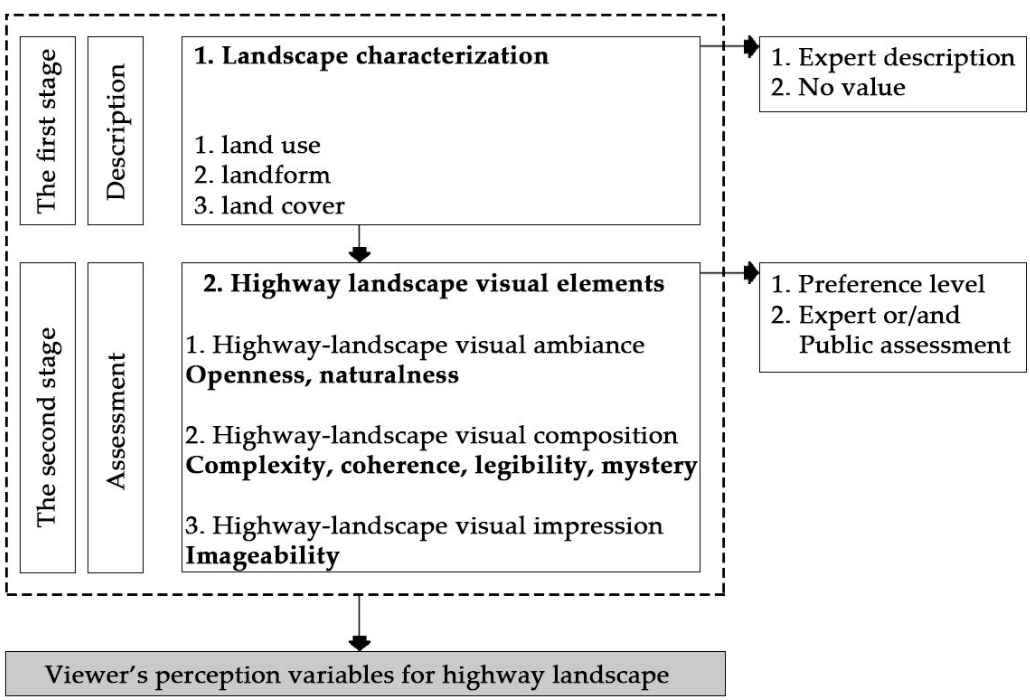

Figure 3. Landscape characterization and perception variables of highway landscape.

4. Discussion

The study initially established an understanding of the landscapes along or around highways and other roads, exploring research objectives and preferences to comprehend the characteristics and elements of highway landscape preferences. Furthermore, this study not only analyzed the methods used to identify these landscape preferences, but also provided a detailed discussion of the variables involved in the methods. In particular, a more complete and unified set of perception variables for highway landscape preferences was summarized and presented, which might have critical applications for future research on highway landscape preferences. Over the years, as the demand for grade-separated transport networks has continued to grow, there has been a significant increase in interest in the physical aspects of highways and their potential impact on viewers [5]. The aesthetics of the landscape perceived by a viewer of a highway depends on the physical and psychological distance between the viewer and the landscape [5]. As a result, transport networks play a crucial role in shaping the landscape character and facilitating human interaction with the landscape.

In this period of profound human impact on the land, roads have introduced novel perspectives on environmental interaction [6]. Landscapes along roadsides, encountered daily by individuals, play a crucial role in introducing individuals to new regions, encouraging the exploration of the surrounding environment, and shaping their perception [42]. Highways, in particular, emphasize the importance of landscape design and environmental regeneration as a medium for integrating natural landscapes and man-made structures [11]. The complexity and diversity in highway landscapes emphasize that they are about more than just transport. The landscape presents diverse natural and cultural features, including forests and historical roadside architecture, offering travelers a distinctive visual and experiential journey. The highway, thus, serves both transportation and leisure purposes.

In terms of their purpose and participants, these studies reveal the importance of considering a variety of perspectives to assess aesthetic aspects and the impact of environmental change. On the one hand, most studies with participants emphasize the subjective nature of a visual preference assessment and the importance of including a wide range of perspectives. On the other hand, studies lacking participants (experts only) highlighted the importance of innovation. However, the hybrid approach promotes a more comprehensive discussion of aesthetic values and stimulates the creation of novel approaches to landscape valuation. Beyond this, investigating visual preferences encompasses not only aesthetics, but also the interaction between sensory experience and environmental perception, particularly in the context of traffic noise.

The visual preference of the highway landscape is pivotal to viewers' experience using the highway, influenced by physical factors, such as patterns of land cover and land use, and individual psychological factors, such as mental information [2]. The assessment of landscape aesthetic preferences is highly subjective due to individual psychological factors; i.e., people's interactions, past experiences, and current landscape characteristics differ in their evaluation of the attractiveness of the same landscape [31]. In general, viewers prefer nature, natural diversity, and historical significance in highway landscapes, while being critical of poorly integrated or maintained cultural elements. This is because highway infrastructure causes anthropogenic changes in the surrounding environment, leading to land use and vegetation alterations and a reduction in greenery [12]. Neglect in managing these landscapes can lead to a cluttered and disorganized appearance, negatively affecting viewers' preferences. Furthermore, the preference for motorway landscapes is influenced by various factors, including the level of highway use, external dynamics such as noise, and the complexity of the factors influencing preference.

The growing interest in the visual quality of highway landscapes began primarily in the mid-20th century in America [10]. During this period, many tourist attractions in America were closely associated with automobile travel, making the highway landscape pivotal to drivers and passengers. As leisure activities on the road increased, the evaluation of the quality of the highway landscape between destinations became increasingly important. It was during this era that the visual assessment of highway landscapes began to be recognized. Three different methods were used consecutively to assess highway preferences. The viewer perception approach is based on subjective experience and aims to reach a consensus on landscape quality. The expert approach uses established criteria and expert knowledge to analyze natural landscape features objectively. The hybrid approach combines objective analyses with subjective experiences to comprehensively understand. This approach emphasizes the multifaceted nature of landscape aesthetics and the importance of using different strategies for assessment.

A highway landscape visual preference assessment comprises a systematic and scientific inquiry into the current state of the landscape environment. The evaluation considers formal aesthetics and highway viewer's values, thus offering a comprehensive overview of the landscape environment along the roadside. Assessing landscape vision is inherently complicated due to the task of capturing the nuanced human perceptual experience, specifically while dealing with transient landscape elements [10]. Human visual cognitive behavior involves more than just gathering external information; it is a complex mental process combining judgments and noticing visible specifics. Scientific evidence emphasizes the significance of the roadside landscape and its visual attributes for road viewers' perceptions [33]. A valid highway landscape assessment system offers a comprehensive assessment and understanding of the environmental conditions in and around the highway [11]. Therefore, this study attempts to propose comprehensive variables for characterizing and evaluating highway landscape characters and their preferences.

5. Limitation and Future Studies

This study systematically reviews viewers' preferences toward the highway landscape. However, this study still has some flaws. Firstly, the study only used qualitative analysis and lacked quantitative analysis. Therefore, it is recommended that future research includes quantitative analysis, such as meta-analysis, further to investigate the published topic in the related field. Next, the number of keywords was limited. In future research, keywords such as "preference criteria", "preference factors", and "preference impacts" could be included to enhance the number of articles and the understanding of preference variables. Lastly, while the study identified the variables influencing highway landscape preferences, it lacked an in-depth discussion, assessment, and validation of each variable. Therefore, it is crucial for future research to explore these variables more deeply, offering adequate theoretical and practical definitions for the preference assessment.

6. Conclusions

This study analyzed 37 papers on landscape preferences for highways and other roads, uncovering that the perception variables of openness and naturalness for the visual ambiance; complexity, coherence, legibility, and mystery for the visual composition; and imageability for the visual impression of the highway landscape have an effect on visual preferences for highways. Viewers' visual preferences may be intuitive and influenced by their personal favorites. Our findings suggest that, while natural landscapes are generally preferred, it is essential to recognize the significance of cultural landscapes for a comprehensive understanding of highway landscape preferences. Although the study has improved the understanding of highway landscape preferences through more refined perceptual variables, a crucial next step involves validating and critically assessing these variables. Employing a preference/scenic quality research approach, professionals and viewers can simultaneously rate the same highway landscapes. This allows the variables and relationships between the differences to be explored and validated. In conclusion, the findings of this study refine the completeness of the perceptual variables of highway landscapes and establish the relevant reference criteria for professionals.

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Appendix A

Table A1. Summary table of all 37 documents.

Ref. No. (No)	Type of Road	Landscape Character in Which the Road Is Embedded	Viewers	Views	Purpose of the Study	Assessment Method	Response Format	Media Used to Represent the View	Criteria or Variables
[1] (1)	Highway	Not detail the specific surrounding landscape character	NO	F	Identifying landscape characters	ER	-	-	None
[2] (2)	Highway	Rounded glacially sculpted hills and ridges, second-growth forests, and so on	N	T	Assessing scenic quality	PR and ER	PQ	CP	Coherence, complexity, legibility, mystery, openness, smoothness, and locomotion
[3] (3)	Highway	A variety of natural and cultural elements	U	F	Evaluating users' preferences	PR	PQ	CP	Natural landscape elements and cultural landscape elements
[4] (4)	Highway	Complex mountainous terrain, hydrology, and geology	NO	F	Assessing landscape character	ER	-	-	Function, aesthetics, ecology, and safety
[5] (5)	Highway	Urban residential areas and countryside agricultural land	U	F	Assessing scenic beauty	PR	S	CP	Variety of vegetation, colorfulness, vegetation type and combination, and perceived importance of various elements
[6] (6)	Highway	Not detail the specific surrounding landscape character	N	T	Assessing landscape character	PR and ER	S	CP and PM	Physical, aesthetic, and psychological attributes
[7] (7)	Highway	Not provide detailed descriptions of each landscape character	NO	F	Assessing scenic quality	PR and ER	OS	CTA	Visual attraction factors and physiological signals
[8] (8)	Highway	Two large physiographic units	U	F	Assessing visual impact	PR	S	CP	Various elements of the highway landscape
[9] (9)	Highway	Not detail the specific surrounding landscape character	NO	F	Assessing visual landscape	PR	ONI	CP	Color tendencies, materials, and recognition degrees

Table A1. *Cont.*

Ref. No. (No)	Type of Road	Landscape Character in Which the Road Is Embedded	Viewers	Views	Purpose of the Study	Assessment Method	Response Format	Media Used to Represent the View	Criteria or Variables
[10] (10)	Highway	Diverse landscapes, including mountain-valley conditions, and so on	N	T	Assessing scenic beauty	PR and ER	SL	CP	Naturalness, vividness, variety, and unity
[11] (11)	Highway	None	NO	F	Assessing landscape character	ER	-	PM	Indicator system that includes landscape features, environmental harmony, and so on
[12] (12)	Highway	Natural and introduced flora/fauna, colors, lines, patterns, and human interventions	NO	F	Analyzing landscape preferences	ER	ONI	OB	Criteria such as the presence of man-made obstacles, perceptual units, and so on
[13] (13)	Highway	Natural and semi-rural residential landscapes	U	F	Assessing visual impact	PR	S	CTA	Various traffic conditions, two types of landscapes, three viewing distances, and sound condition
[20] (14)	-	-	-		Reviewing in assessing visual landscape quality	ER	-	-	-
[22] (15)	Highway	A diverse landscape, including vast forests and mountain ranges	NO	F	Assessing landscape character	ER	ONI	CP	Landscape visual qualities and natural features
[23] (16)	Highway	Relief and vegetation type	NO	T	Assessing landscape character	ER (CM)	-	GIS and PM	Visual landscape character, such as coherence, complexity, and so on
[24] (17)	Highway	Not detail the specific surrounding landscape character	U	F	Understanding scenic quality	Pr	PQ	CP	Types of vegetation on road verges
[25] (18)	Highway	Mountains, lakeside cliffs, dense forests, diverse topographical features, and several rivers	NO	T	Assessing landscape character	ER (CM)	-	CTA	Visual magnitude
[26] (19)	Great ocean road and highway	Diverse elements such as individual trees, forests, water, beach shores, etc.	NO	F	Assessing landscape character	ER (CM)	-	CP	Road segments, including road orientation, relative elevation, openness, distance to horizon, and the presence of specific elements

Table A1. *Cont.*

Ref. No. (No)	Type of Road	Landscape Character in Which the Road Is Embedded	Viewers	Views	Purpose of the Study	Assessment Method	Response Format	Media Used to Represent the View	Criteria or Variables
[27] (20)	Scenic road	Hilly terrain, three sizable rivers, valleys, and extensive wetlands	N	F	Assessing landscape preferences	PR	PQ	SL	Water, open views, mature trees, stone walls, geologic features, agricultural uses, historic areas, and residences
[28] (21)	Scenic road	A mix of natural and pastoral scenes, forested areas, and open vistas	U	F	Exploring aesthetic characteris-tics	PR	PQ	CP	Motorists' aesthetic experiences, emotional responses to the parkway's design, landscape variety, scenic beauty, and overall driving experience
[29] (22)	Highway	Natural and residential landscapes	U	F	Assessing visual impact	PR	PQ	CTA	Levels of noise emission, two levels of HGV percentage in traffic composition, and three distances to the road
[30] (23)	Rural road	A mixture of agriculture and forestry	N	T	Assessing the visual quality	PR	OS	CP	Landscape characters
[31] (24)	Rural road	A variety of landscapes, such as agricultural fields, forests, and water bodies	U	F	Assessing the visual quality	PR	OS	CP	Agriculture in the forefront with forest in the background, bare ground in the forefront with forest in the background, and so on
[32] (25)	Urban street	A mix of modern and historic elements in an urban setting	U	F	Exploring visual preferences	PR	S	CP	Complexity, coherence, and imageability
[33] (26)	Urban street	Poplar planting	N	T	Understanding visual preferences	PR	S and ONI	CP	Naturalness, variety, impressiveness, eye-catchiness, harmony, interest, and excitement
[34] (27)	Urban street	A mix of residential, commercial, and administrative areas	NO	T	Assessing visual quality	ER (CM)	-	CTA	Objective indicators and subjective indicators
[35] (28)	Urban street	A mix of high-rise buildings, commercial districts, skyscrapers, parks, and so on	NO	T	Analyzing visual perception	PR and ER	S	CP	Salient region saturation (SRS), visual entropy (VE), green view index (GVI), and sky-openness index (SOI)
[36] (29)	Urban street	Urban greenery alongside roads	N	T	Assessing visual quality	PR	S	CP	Complexity, interference to coherence, stewardship, naturalness, and beauty impression

Table A1. *Cont.*

Ref. No. (No)	Type of Road	Landscape Character in Which the Road Is Embedded	Viewers	Views	Purpose of the Study	Assessment Method	Response Format	Media Used to Represent the View	Criteria or Variables
[37] (30)	Urban–rural road	Agricultural land	N	T	Understanding landscape preferences	PR	OS	BWP	Typical development, development with trees, and natural additions like trees and prairie plants
[38] (31)	Scenic road	Sightseeing locations, nature and woods, fields, water bodies, and mountains.	N	T	Assessing driving experience	PR and ER	PQ	CP	Sightseeing, nature and woods, fields, water, and mountains
[39] (32)	Highway	Urban	NO	F	Assessing landscape character	ER	-	-	Various factors related to green infrastructure
[40] (33)	Urban street	Not detail the specific surrounding landscape character	NO	T	Assessing landscape character	ER (CM)	-	CTA	Security, depression, vitality, and aesthetic perceptions
[41] (34)	Urban street	None	NO	-	Assessing visual quality	ER	-	-	Identifying and describing twelve visual characteristics
[42] (35)	Major roads	Not detail the specific surrounding landscape character	U	F	Assessing landscape character	PR and ER	OS	CTA	Variety, aesthetic of flow, legibility, and orientation
[43] (36)	-	-	-		-	-	-	-	-
[44] (37)	-	-	-		Conceptualizing what landscape values mean in practice	ER	-	-	Aesthetic, economic, natural significance, recreation, cultural significance, and intrinsic values

Notes: Viewers: Users abbreviated as U (e.g., drivers, passengers, pedestrians/bicyclists, etc., with views from the road). Neighbors abbreviated as N (e.g., residents, recreation participants, pedestrians/bicyclists not using the road, students at school, shoppers, etc., with views toward the road). None (without users) abbreviated as NO. Views: From the highway, urban street, rural road, etc., abbreviated as F. Toward the highway, urban street, rural road, etc., abbreviated as T. Assessment method: Public ratings abbreviated as PR. Expert ratings abbreviated as ER. Public ratings and expert rating abbreviated as PR and ER. Computer model (e.g., GIS) abbreviated as CM. Response format: Paper questionnaire abbreviated as PQ. Survey abbreviated as S. Online survey abbreviated as OS. On-site investigation abbreviated as ONI. Slide abbreviated as SL. Media used to represent the view: Color photographs abbreviated as CP. Black and white photographs abbreviated as BWP. Photo-based method abbreviated as PM. Computer technical assistance abbreviated as CTA. Slides abbreviated as SL. Observation abbreviated as OB.

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