

Article

Study on Multiscale Virtual Environment Construction and Spatial Navigation Based on Hierarchical Structure

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Abstract: Multiscale virtual environments (MSVEs) allow the integration of elements and environments at different scale levels into a unified space, which facilitates researchers' perception, understanding, and experimental research of complex geospatial spaces. Although there have been several methods for achieving multiscale effects in virtual environments (VEs), they cannot assist users in constructing more complete spatial cognitive maps and presenting multiscale information efficiently. This study proposes a hierarchical-structure-based MSVE construction method, which can effectively integrate multiscale information and ensure that the richness of details of information is gradually enhanced with the progression of the hierarchical structure. In addition, a spatial navigation study is conducted, considering the relationship between users' perspective changes and spatial cognition, and the effects of users' perspective changes on their spatial cognition in an MSVE are explored. A multiscale virtual wetland environment covering four levels is constructed to conduct a case study of a virtual environment of a wetland of Poyang Lake. The research results show that the proposed method is feasible. Moreover, the spatial navigation based on the change in the hierarchical perspective is in line with the spatial cognitive habits of users, which can satisfy the cognitive needs of users from the macro-region to specific wetland landscapes.

Keywords: VE; hierarchical structure; wetland; spatial navigation; spatial cognition



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1. Introduction

With the continuous development of three-dimensional (3D) modeling technology and virtual reality (VR) technology, immersive virtual environments (VEs) have been widely used in the fields of healthcare, architecture, urban planning, tourism, gaming, and natural sciences [1]. However, most of the research on three-dimensional virtual environments (3DVEs) has focused on a single scale, and there have been certain challenges in presenting multiscale virtual scenes and modeling information richness. Therefore, how to effectively design and present MSVEs to navigate and roam in MSVE to satisfy users' spatial cognition is an urgent problem in the field of VE development.

Unlike single-scale VEs that focus on the information at a particular spatial scale, MSVEs can encompass different scales within the same project, summarize and balance the whole picture, and provide more detailed and richer information across multiple scales. A space navigation mission is a technique designed to determine the current location or to navigate to the desired location. Spatial navigation is of great importance in the VE field, as it provides the basis and tools for users to interact and explore VEs, enabling a better use and experience of VR [2]. In real-world environments, spatial navigation can be realized through reading navigation maps, signs, and landmarks at different scales; these instructions provide different levels of information to influence a user's spatial cognition and perform well in cued spatial navigation tasks [3]. However, human cognitive

abilities for large-scale spaces or unfamiliar environments have still been imperfect. In VEs, spatial navigation tasks are usually influenced by a user's visual perception and cognitive information about space. Moreover, directly traversing the complete virtual space can be challenging for users, and applying basic methods (e.g., scale changes, rotation, and scaling) makes it difficult to explore target information in VEs. In addition, the lack of accurate positioning systems in virtual scenarios prevents spatial navigation techniques in real environments from scaling well to large virtual worlds. To solve this problem, this study proposes a hierarchical structure to construct an MSVE, which can realize the integration of multiscale elements into the VEs in the same public space, along with the progressive transformation of a user's point of view to help the user to complete the navigation task in the VEs and establish a complete spatial awareness and cognitive map [4]. Montello proposes four core classes of psychological spaces based on the size of the space in relation to the human body (i.e., its projective size). They show how people perceive and process spatial data based on the relative scale of space, and the essential differences in the mental processing of these spatial categories [5]. A deeper understanding of the classification of these mental spaces and their attributes is essential to mastering the development of spatial perception and navigation skills. For example, considering spatial attributes at different scales when designing a geographic information system (GIS) can more accurately meet users' needs and enable the more effective communication and understanding of spatial information.

Further, based on the characteristics of the adopted hierarchical structure and the properties of psychological spaces, this paper focuses on the fusion method of multiple levels of VEs to construct an MSVE. Moreover, through coupling the relationship between progressive shifts in users' perspectives and spatial cognition, a study of spatial navigation in MSVEs is conducted. In this study, spatial navigation is regarded as a process of a gradual increase in elemental details and spatial cognitive information observed by a user and a process of the gradual refinement of the user perspective from the spatial extent to specific wetland landscape scenes rather than to the specific path navigation and planning. The combination of virtual spatial cognition and the progressive transformation of a user's perspective ensures that each level (including the wetland extent and wetland landscape) is naturally connected and smoothly transitioned so that different content effects are presented at different scale levels. The feasibility of the proposed hierarchical structure and spatial navigation research of MSVEs is verified through an experimental case study of a VE in the Poyang Lake wetland. The experimental results show that the application of a hierarchical structure to the MSVE design can effectively present the information content of different scales, and the hierarchical structure has stability and high scalability, which is conducive to the spatial architecture of the network platform. The incremental shift of perspective approach based on the spatial hierarchical progression conforms well with human spatial cognitive laws. The main contributions of this research are as follows:

1. Considering the characteristics of the level of detail, this study proposes an MSVE construction method based on a hierarchical structure and the properties of psychological spaces, which can present information at different scales efficiently and ensures that the richness of the details is enhanced with the progression of the hierarchy;
2. This study combines the progressive shift of a user's perspective with spatial cognition and adopts different navigation strategies to realize multiscale spatial navigation tasks in VEs at different levels to satisfy the overall user cognition from a large scale of the spatial scope of the wetland to the small-scale local details of the wetland landscape, which is in line with human spatial cognitive habits;
3. The stability, scalability, and strong applicability of the proposed hierarchical structure are verified by experiments, and the results show that the proposed design method can be employed to satisfy virtual scenarios of multiple scales and complexities.

The rest of the paper is organized as follows: Section 2 reviews the related work on MSVE technology and space navigation in VEs. Section 3 explains in detail the MSVE construction and spatial navigation design based on a hierarchical structure. Section 4

presents the application of the methodology through an experimental case study. Section 5 discusses the application potential of the proposed method. Finally, Section 6 summarizes this study and presents future research directions.

2. Related Work

2.1. Concept of Scale

The concept of “scale” has become increasingly popular with the deepening of geographic research. In multiscale research, the term “scale” relates to the relationship between spatial extent and spatial information. Smaller-scale environments provide detail and precision, enabling users to easily identify and process specific objects and tasks; meanwhile, larger-scale environments provide a broader scene and overall perception, enabling users to obtain a more macro perspective and understanding. The proposed hierarchy-based approach to the MSVE design allows for an in-depth analysis of the “scale” concept and classes of psychological spaces, that is, spatial and hierarchical dimensions and scope components in the category of observation [6]. Finally, realizing changes in the scope and hierarchical level of the VEs with user participation and control helps users to construct a complete map perception and, thus, improves their spatial understanding.

2.2. Multiscale Methods in VEs

The VEs overcome the temporal and spatial limitations of traditional maps and allow for studying cross-scale spatial knowledge and spatial tasks, which can, thus, be better presented and experienced by users in VEs [7]. Multiscale approaches in VEs for spatial navigation applications can not only enhance the combined visual and cognitive experience of users but also facilitate their exploration and understanding of VEs [8]. The application of multiscale methods to VEs has become more widespread and mature in recent years. In view of that, this study discusses the development of multiscale methods in a three-pronged overview of multiscale techniques, functions, and auxiliary equipment in VEs, as shown in Table 1, focusing on the application of multiscale methods to the VE construction and space navigation design.

Table 1. The main approaches for realizing multiscale in VEs.

Type of Multiscale Method	Method	Details
Multiscale technology	Hierarchical spatial division algorithms	Quadtree and octree algorithms
	Detail-level display methods	LOD, HLOD, and Nanite technology
Multiscale function	Viewpoint manipulation	Zooming, viewpoint switching, and free roaming
	Semantic query	Target information and object index
	Map navigation	Mini-map, directional markers, glowing trajectory, and flight experience
Auxiliary equipment	Interactive equipment	Spatial tracking devices, wearable devices, gesture recognition, and controllers

Multiscale techniques for VEs mainly include hierarchical spatial division algorithms and detail-level display methods. Hierarchical spatial division algorithms comprise quadtree and octree algorithms [9,10], which have been commonly and efficiently used to manage and query data structures and spatial division methods. Extending these algorithms to immersive VEs allows for performing time-efficient navigation wayfinding computations by combining navigational map structures with simulated terrain scenarios. In addition, an octree-based structure can effectively support viewpoint correction algorithms to adjust rapidly to the positional changes of a user’s viewpoint, which lays the foundation for smooth and collaborative human–computer interaction in VEs. The level-of-detail display methods include the Level of Detail (LOD), Hierarchical Level of Detail (HLOD), and Nanite methods. The LOD method is typically used to describe the degree

of detail in the presentation of an object at different distances or scales and represents an important concept in the fields of computer graphics and VEs [11]. This method aims to achieve the best possible realism and visual quality while maintaining a high performance by dynamically adjusting the level of detail of objects in a VE. The LOD methods have often been used on top of a single model, but the performance and memory consumption of rendering large-scale virtual scenes has resulted in the development of the HLOD method, which represents a technique that extends the LOD concept. The HLOD method enables more efficient rendering compared to LOD, as well as rendering by organizing scene objects in levels so that a scene can be rendered at different levels of detail at various distances or scales. Nanite technology employs an innovative infinite geometry rendering technique for large-scale, high-resolution models, and there is no need to pre-segment models, which saves storage and computing resources. Moreover, it has the ability to maintain high-precision detail information on a VE, making the rendered results more realistic and lifelike. The aforementioned methods have been mainly applied to single-scale VEs to solve the problems of scale adaptation and visualization effects in VEs and display information with different details through the distance display function.

In recent years, multiscale functions in VEs have been designed to realize different scale expressions and operations, including viewpoint manipulation and semantic query map navigation, so users can select appropriate scale information according to their needs. Viewpoint manipulation extends the functions, such as zoom browsing and the viewpoint switching of two-dimensional maps, to VEs to achieve the free switching of observation positions and viewpoints in the VEs, as well as to obtain a detailed rendering of elements, such as scenes and models, or a global view to adapt to multiscale observation and experience. For instance, Yu et al. [12] used a forest landscape 3D visualization platform (FLV) to visualize the forest landscape of Changbai Mountain from individual trees to forest stands at the landscape scale continuously and from individual years to decades and centuries at the time scale by switching the viewpoints. In an MSVE, hierarchical information allows for organizing and presenting data and information at different scales according to a particular hierarchical structure. Namely, through semantic querying, users can make selections to access and analyze their target information according to their needs, which provides an efficient solution for spatial navigation and localization in VEs [13]. With the development of VR technology, users have been increasingly requesting the ability to move freely through VEs; nevertheless, many novices have often been unable to locate objects and positions because of a virtual scene's size. Therefore, using map-guiding features, such as mini-maps, directional markers, glowing trails, and flight experiences from a drone's point of view, can help users move around in a virtual scene and understand the environmental layout [14]. However, these features pose certain challenges to computer performance, storage, the rendering effectiveness of virtual scenes, and human–computer interaction.

The application of assistive devices, in addition to functionality, allows for multiscale human–computer interaction operations in VEs, including spatial tracking devices, wearables, gesture recognition, controllers, and other external assistive devices. Spatial tracking devices can track the position of a user's head and body to enable a multiscale experience of space [15]. A head-mounted display (HMD) has been used to provide an immersive VR experience. Gesture recognition and multi-touch control interfaces can also be used for graphical interface management and spatial navigation in MSVEs [16]. Moreover, other external assistive devices (e.g., mice, keyboards, and joysticks) can also be applied to an MSVE. By using assistive devices, users can control their positional movement and freely explore different areas and scenes in a VE to complete spatial navigation and interaction, which helps participants construct spatial awareness and cognitive maps [17].

2.3. MSVE

An MSVE is a type of virtual scenario that maps multiple realistic environments at different scales to a computer world and integrates elements with different levels of scale and detail into the same shared space [18]. Unlike single-scale VEs, MSVEs can

simulate multiple spatial scale scenes and situations in the real world, providing users with information on a complete and coherent spatial structure and spatial cognitive experience. For instance, Hildebrandt et al. [19] constructed a multiscale virtual 3D city with seven levels, including cities, districts, quarters, boroughs, neighborhoods, blocks, and buildings. Li et al. [20] constructed a multiscale forest landscape from the stand scale to the forest using 3D reconstruction techniques. Further, Jia et al. [21] assembled simple models into complex multiscale virtual scenes, combining information fusion, multiscale correlation, and multi-scene iteration techniques. Finally, Felix et al. [22] created a multiscale virtual coastal environment to simulate the effects of climate change on coastal vegetation and species distribution. The above studies are important for promoting spatial awareness, improving navigation efficiency and facilitating human–computer interaction, but how to effectively integrate data into MSVEs and present it in a way that is consistent with human spatial perception is also a current challenge. Therefore, in the development of a reasonable MSVE design method, the integration of information of different scales and the optimization of the comprehensive presentation effect must be comprehensively considered.

2.4. Spatial Navigation in MSVE

An MSVE contains objects with variations of a very large scale that make the task of spatial navigation in VEs extremely challenging. Namely, different navigation speeds and steering angles can cause difficulties in navigating to the target position in VEs. Recent research has provided certain insights into the study and design of spatial navigation in VEs [2]. Therefore, adding multiscale spatial interactive navigation to VEs can effectively enhance the user experience in a large virtual world. The spatial navigation functions in an MSVE enable users to observe the structure and organization of VEs and locate and navigate them on demand. This allows users to acquire spatial knowledge and move between scales in an easier and more efficient way. At the same time, virtual scenarios can create highly flexible and immersive research environments, and human space navigation research increasingly relies on experiments with virtual scenarios [23]. For instance, James et al. [24] employed a cube mapping method for the multiscale spatial navigation of 3D scenes, providing improved flexibility and ease of use for VE navigation. Subsequently, Trindade et al. [25] improved the navigation of a cube mapping structure, providing information about the surroundings at each moment and, thus, reducing navigation errors. Huang et al. [10] corrected the position of a mobile VR viewpoint to correspond to a user's viewpoint in real time using a viewpoint correction algorithm, and roaming flights were applied to multiscale navigation. Using the adaptive adjustment of navigation speed ensures an optimal navigation experience at every scale level. Moreover, the combination of human–computer interaction operations based on VR devices provides a dynamic visualization scheme for MSVE navigation [26]. The complexities of MSVEs have significantly advanced navigation research. However, employing navigation methods that do not align with users' cognitive patterns can increase the cognitive load. Therefore, designing effective MSVEs requires achieving a balance between information presentation and users' cognitive capabilities.

3. Hierarchical MSVE Design and Spatial Navigation

The workflow considered in this study is presented in Figure 1. First, the data collected and processed for the construction of the VE are elaborated (Figure 1a). This process includes multiple types of wetland metadata, data collection tools, and data processing procedures. Then, the hierarchical model is designed and described (Figure 1b), and the integration of components for constructing a complete MSVE is elucidated (Figure 1c). Finally, a representative wetland virtual scene is constructed to extend the application of a multi-device virtual experience, and a perspective-based progressive spatial navigation strategy study is conducted (Figure 1d).

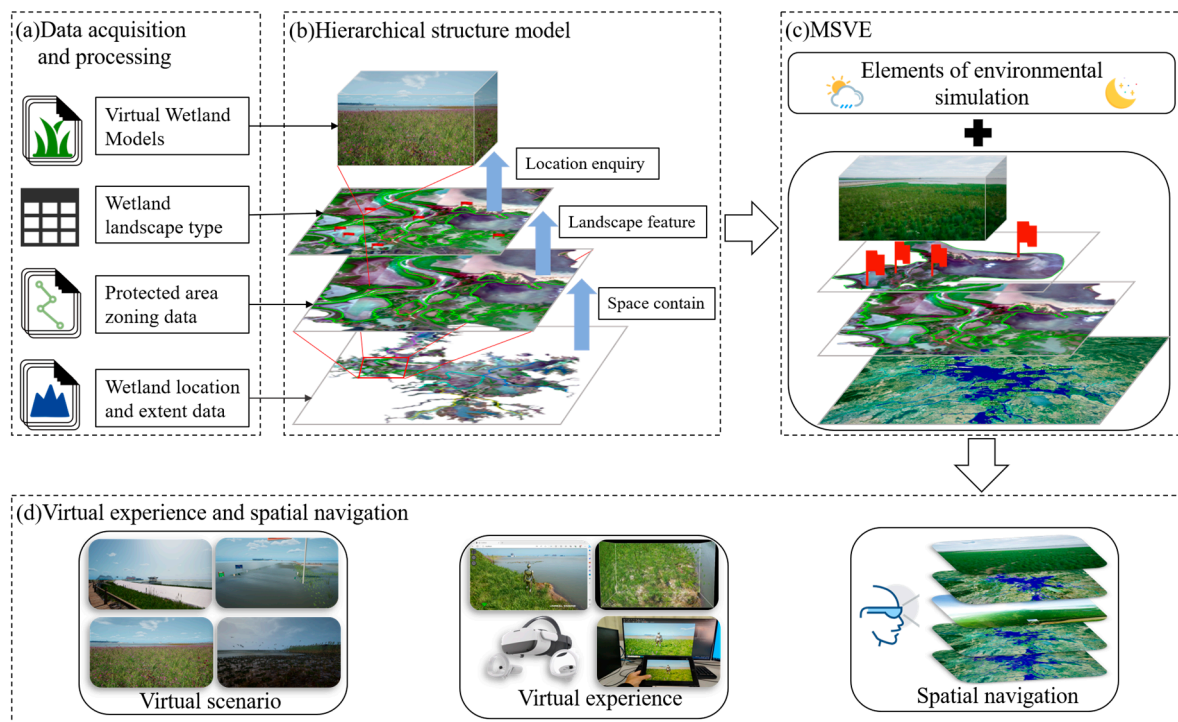


Figure 1. Workflow of MSVE construction and spatial navigation. Red symbols are site locations showing typical wetland landscapes.

3.1. Necessity of MSVE Construction and Spatial Navigation

The MSVEs are often complex and depict information at multiple scales, so an effective construction method and spatial navigation system are crucial to maintaining the user experience. First, by constructing an MSVE, different levels of information can be fused to provide a comprehensive perspective and help users understand complex spatial information [27]. Second, in an MSVE, users could rapidly switch from one scale to another, which might cause them to become disorientated or not understand the current contextual scene. Therefore, efficient construction methods and spatial navigation designs could help users maintain a sense of direction and contextual continuity during transitions and ensure that progressive user perspective shifts based on spatial hierarchies are consistent with human cognition. Third, the scale of VEs and the amount of data have a significant impact on both a user's decision-making of spatial judgments and constructing spatial cognition [28]. The approach and spatial navigation of hierarchies in combination with different types of psychological spaces can help users locate a target object or information rapidly in a massive amount of data, thus avoiding the problem of the spatial information overload or low corresponding speed that can occur due to the massive data loading.

Considering the necessity of MSVE construction and spatial navigation, although the existing spatial navigation tools can assist users in spatial navigation tasks, they essentially add additional functionality to a VE, which not only increases memory pressure but also reduces a computer's responsiveness. To this end, this study proposes a design that integrates spatial navigation tasks from the construction of virtual scenarios, which differs from traditional spatial navigation tools.

3.2. Proposed MSVE Design

Users usually go through cognitive processes from global to local and from large to small scales when navigating spatially in VEs, and people naturally organize cognitive processes into hierarchical structures [19]. A hierarchy represents an organizational structure where spatial information is organized into manageable units of different scales, where each level denotes spatial information and models at a different level of detail [29]. There

are certain correlations and connections between neighboring levels, making spatial information easier to understand and remember. The concept of psychological space has been used to describe the subjective experiences that individuals psychologically construct about themselves and their environment [30]. Montello distinguishes four classes of psychological spaces: geographical, environmental, vista, and figural space [31]. Geographical space is projected onto a much larger scale than the human body and must usually be understood through symbolic representations. In relation to the human body, ecological space is a larger space that surrounds the body, such as a region or a city. Vista space corresponds to or is larger than the human body in projection. It is a space that can be observed through visual perception from a fixed location without significant movement. Figural space is a space that can be perceived and observed directly and often includes small 3D spaces. Such delineations have profound effects on human spatial perception, thinking, memory, and behavior, and provide clues for the design of effective spatial information systems and user interfaces.

Therefore, an MSVE construction method based on the hierarchical structure is proposed for the VE design in this study. The proposed method divides a VE into different levels, each of which corresponds to a specific psychological space characteristic. Meanwhile, it should be emphasized that spatial navigation is a process of the gradual refinement of spatial information and model details, as well as of a user's spatial perceptions with progressive changes in perspective. Considering the unique natural characteristics of wetlands, the design and construction of MSVEs are systematically divided into four levels according to the four mental spaces, namely, the wetland extent, conservation area delineation, landscape type classification, and virtual wetland scenarios, as shown in Figure 2. These four levels of information fully satisfy the demands for wetland knowledge and management and cover information at different scales from the macro to micro level, describing in detail the basic attributes of wetlands, management zoning, eco-system diversity, and changes in wetland landscapes. This type of design allows users to observe the scene content at different scales with different levels of detail and progressively move from single-scale to multiscale 3DVEs. The four levels are as follows:

- L0: Geographical space and wetland extent. A wetland is usually a broad area that encompasses a general spatial pattern and various geographical features. A large lake can be considered a geographical space because it occupies a large enough space and often requires symbolic representation to be recognized and understood. People must rely on maps or other forms of symbolic representation to understand and navigate such spaces;
- L1: Environmental space and nature reserves in wetlands. The delineation of protected areas involves specific parcels of land and regions that comprise unique wetland ecosystems. These areas are usually large enough that they cannot be fully grasped from a single perspective, but perception can be gradually built up by navigating within the area and accumulating spatial information. Protected areas can, therefore, be considered environmental spaces;
- L2: Vista space and wetland landscape types. The classification of landscape types involves identifying and categorizing different landscape elements within a wetland, such as watershed landscapes, wetland vegetated landscapes, wetland geomorphic landscapes, and man-made landscapes. These landscapes visually occupy a larger space, but can allow the observer to view and understand the structure and function of the ecosystem within the wetland from a single point;
- L3: Figural space and virtual wetland scenarios. Virtual wetland scenarios are simulated environments created using digital technology that include the detailed modelling of wetland elements (e.g., monoculture vegetation) and dynamic simulations of changes in ecological processes. These 3D scenes are typically displayed on VR devices and allow users to simulate observation, exploration, and interaction with multiple model details and dynamic changes in the scene.

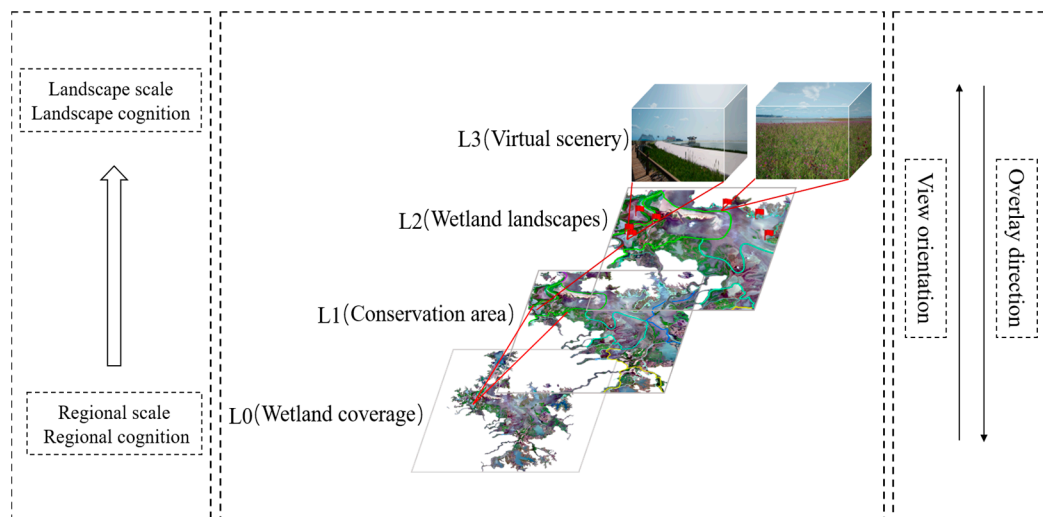


Figure 2. The MSVE based on a hierarchical structure. Red symbols are site locations showing typical wetland landscapes.

The characteristics of the level of detail for the optimization of a virtual scene are considered in each level, and increasing the degree of the LOD level indicates that the 3D geometry is enriched in terms of more detailed content. Therefore, the idea that different LODs can present detailed information about the model is referenced in the design of the spatial hierarchy of the MSVE [19]. The richness of spatial information is integrated in a hierarchical architecture from a low to high level in a stacked architecture to form an MSVE. In this architecture, the four levels can be viewed and experienced as four single VEs. The levels can also be connected; a user can easily switch between the different levels by adjusting the viewpoint to achieve the multiscale navigation of a VE. L0 represents the reserve zoning through a spatial extent inclusion relationship to L1; L1 queries the wetland landscape types within the reserve based on the spatial information to L2, and the user enters the virtually reconstructed wetland scene (i.e., L3) based on the index of the target point of interest in L2. The path from L0 to L3 is the design path for view orientation and spatial navigation. From the regional scale to the landscape scale, a virtual scene becomes richer in detail, and the spatial cognitive process improves as a user's perspective gradually deepens. L0 is a homepage interface, whereas L3 is an immersive 3D virtual scene, which progresses from the overall scope of the wetland to the specific wetland landscape scene in a gradual manner to satisfy users' spatial cognition needs from the region to the landscape. L3 to L0 represent the design direction and overlay direction of the hierarchy. Each level is superimposed on the top of the previous level; in other words, smaller scales are nested within larger scales. The use of data downscaling visualization methods makes L0 the bottom level of the proposed hierarchical design but the first level of the perspective presentation [32].

4. Case Study

4.1. Study Area and Data Acquisition

Poyang Lake, located in the north of Jiangxi Province, on the south bank of the Yangtze River, which is the largest freshwater lake ecological wetland in China, was selected for a case study in this work. Its geographical co-ordinates are between 115°47' and 116°45' East longitude and 28°22' and 29°45' North latitude, in the subtropical monsoon climate zone, as shown in Figure 3. The whole lake area has the shape of a gourd, with a length of 173 km and a width of 16.9 km. At its widest point, it is 74 km wide, and, at its narrowest point, it is 3 km narrow [33]. It is divided into northern and southern parts with the Songmen Mountain as a boundary. The northern part is the narrow mouth of the lake connected with the Yangtze River, and the southern part is the main lake area, with the Rao River

from the east, the Xin River from the southeast, the Gan River and the Fu River from the southwest, and the Xiushui River from the northwest, which is injected into Poyang Lake. The topography of the lake bottom of Poyang Lake is flat, high in the southwest and low in the northeast, with a microscopic undulating topography.

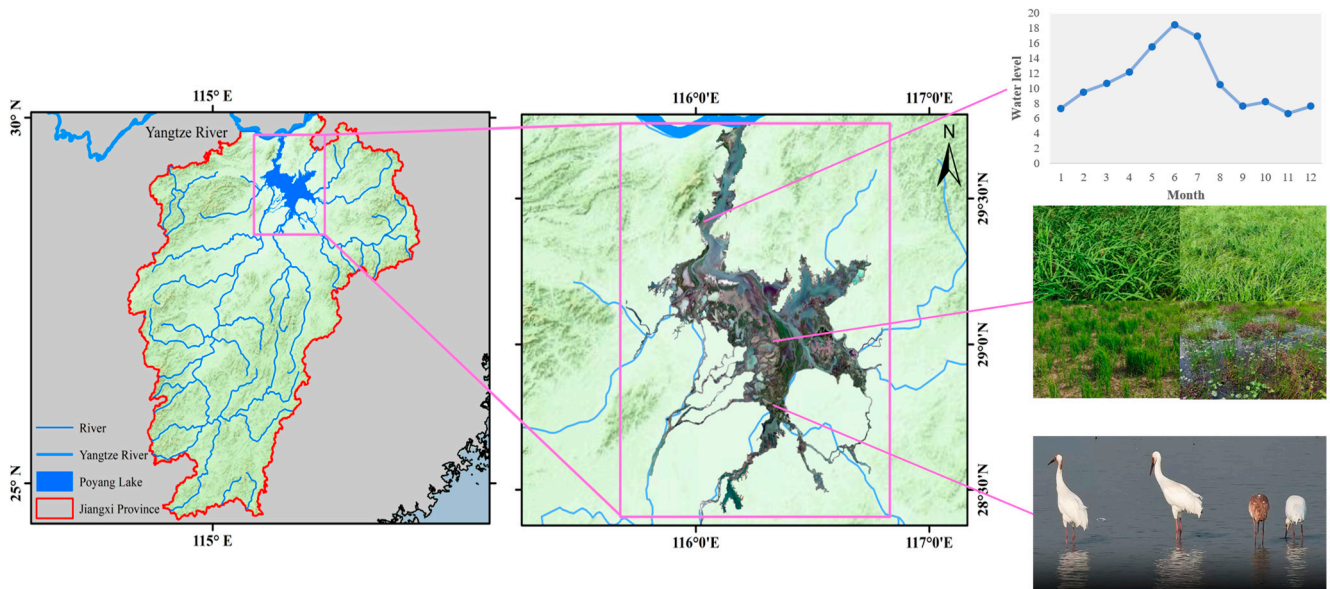


Figure 3. The study area.

Poyang Lake is under the joint influence of the subtropical monsoon climate, five rivers, and the Yangtze River, and the lake's water volume, water level, and flow rate exhibit unique seasonal fluctuations [34]. The period from April to September is a period of abundant water, warm and rainy climate characteristics, and the accumulation of tributaries and the backwater of the Yangtze River; Poyang Lake has a huge area of water and a huge amount of water storage. In contrast, the period from October to March is a period of reduced water supply, and, in this period, the lake shrinks significantly in size, presenting a withered and desolate scene. For instance, for Xingzi Station, the highest water level of 19.41 m was reached on 23 June 2022, and the lowest water level of 6.67 m was reached on 7 November of the same year [35]. Therefore, the wetland of Poyang Lake can be described as one plane of high-water level and one line of low-water level. The special changes in hydrological processes make Poyang Lake have rich vegetation types, including aquatic plants, marsh plants, and mudflat plants, according to the “China Wetland Classification System” and the classification standard of the Poyang Lake wetland [36]. Fluctuations in the water level also affect the seasonal succession of vegetation. In spring and summer, the vegetation sprouts and grows; however, the water level increases rapidly, so most of the plants become drowned and eventually die. Nevertheless, in autumn and winter, “water falls out of the beach”, forming numerous shallow lakes and continental beaches, and the wetland herbaceous plants begin to grow rapidly again, creating a different and vibrant scene in the depressed winter. The formed shallow lakes and continental beaches denote rich food resources and habitats for many migratory birds. As a unique lake wetland ecosystem, the Poyang Lake Wetland is an important stage of the East Asia–Australia Flyway (EAAF), providing important habitats for millions of globally important migratory waterbirds [37]. Wintering migratory birds arrive on schedule in early October, usually peaking in number in December, and migrate away by April of the following year. In addition, this lake is a winter home of several critically endangered species, threatened species, and some rare migratory birds on the International Union for Conservation of Nature (IUCN) Red List of Threatened Species [38].

High-variability remote sensing images can present a distribution pattern of wetland landscapes, such as vegetation, water bodies, and islands in the wetlands of Poyang Lake on a large scale. To present the undulations of the wetland topography more accurately, this study acquired the digital elevation model (DEM) data using UAV photogrammetry. The National Catalogue Service for Geographic Information (NCSGI) platform acquires vector data, such as the boundary range of a wetland, rivers, and lakes of Poyang Lake, which can be used to define the scope and process the collected images. This study employed a variety of equipment, such as unmanned aerial vehicles (UAVs), scanners, and digital cameras, to obtain data on wetland elements, including surface texture, water bodies, and vegetation in the wetlands of Poyang Lake. Specifically, 12 different types of wetland surface textures, including mudflat, sand, and grassland, and typical representative wetland vegetation, such as Reeds, *Imperata cylindrica*, *Triarrhena lutarioriparia*, *Carex cinerascens*, and *Polygonum criopolitanum*, were considered. In addition, webcams and field surveys were used to collect information on migratory birds, such as Tundra Swans, Siberian Cranes, and Oriental White Storks, including data on footage of migratory bird postures and habitual movements. Finally, a web query was used to obtain weather data in the experimental area in real time. Detailed data used in the case study are shown in Table 2.

Table 2. Details of data acquisition.

Data Type	Data Content	Data Format	Acquisition Method
Remote sensing images	Poyang Lake area's high-variability remote sensing image with a resolution of 0.8 m	TIFF	High-variability satellite (HVS)
Topographic data	DEM data on the Poyang Lake Wetland Area	TIFF	Remote sensing imagery/UAV
Poyang Lake Wetland Boundary	Vector data on the extent of the wetland boundary of Poyang Lake, rivers, and lakes	SHP	https://www.webmap.cn/ (accessed on 4 September 2023)
Wetland surface texture	12 wetland surface textures, including mudflat, sand, and grassland	PNG	UAV/Digital camera
Wetland waterbody	Images of the lake during calm and rippling periods	PNG	UAV
Wetland vegetation	Variety of typical wetland vegetation, including different growth periods and polymorphic materials	OBJ/PNG	3D scanner/Digital camera
Man-made construction	Buildings and man-made landscapes at virtual set reconstruction sites	PNG	UAV/Digital camera
Migratory bird material	Information on the postures and habitual movements of typical migratory birds	MP4/PNG	Webcam/Digital camera
Weather data	Weather data on the Poyang Lake area, the update frequency is 2 h/time	TXT	Web crawling

4.2. MSVE Construction

In the proposed hierarchical design, L0 represents a base level and a home page for users to enter the VEs. Therefore, the design of this level focuses on accurately locating and presenting the spatial pattern of the experimental area. To this end, this study used the high-resolution remote sensing imagery and DEM of the wetlands at Poyang Lake, which were carefully processed to facilitate a clear definition of the extent of the wetland boundaries and changes in topographic relief. The DEM data were optimized and processed into a 3D terrain model, and the remote sensing data were used for image enhancement, color correction, and edge detection. The remote sensing image rendering was adopted in the terrain 3D model and used in L1 to ensure that users could identify the contour extent, spatial distribution, and topographic relief changes in the wetland in the VEs. In this way, not only could the spatial location of the wetland of Poyang Lake be accurately reproduced

in the VE, but it also provided users with an intuitive reference, helping them understand and recognize the extent and the characteristics of the land and water distribution of the wetland. Moreover, L1 met the users' cognitive needs for the 3D topography of the wetland.

Based on the previous level (L0), the wetlands of Poyang Lake were penalized in L1 according to the nature reserve boundaries of the protected areas within the Poyang Lake area, including six protected areas, such as the Poyang Lake National Nature Reserve (PLNNR), Poyang Lake Nanji Wetland National Nature Reserve, and East Poyang Lake National Wetland Park. Each protected area was clearly defined according to its geographical location and landscape characteristics, which helped to present the spatial containment relationships and data management and query of wetlands in the protected area sub-region and meet a user's cognitive needs of the protected area.

L2 included a diverse range of landscape types in wetland reserves, categorized according to their ecological character and environmental composition. This level included watershed landscapes (e.g., lakes, rivers, and watercourses), wetland vegetation landscapes, wetland animal habitat landscapes, wetland-specific geomorphological landscapes (islands), and man-made landscapes (viewpoints). Table 3 presents the wetland landscape data on 67 locations in the Poyang Lake area. Panoramic images of the same location were synthesized and presented in L2 of the VE as a cube mapping, as shown in Figure 4.

Table 3. Typical wetland landscape zones and their number of landscape selections.

Wetland Conservation Zone	Number of Wetland Landscape Selections
PLNNR	11
Poyang Lake Nanji Wetland National Nature Reserve	12
East Poyang Lake National Wetland Park	10
Duchang Migratory Bird Provincial Nature Reserve	5
Yugan-Kangshan Migratory Bird County Nature Reserve	10
Five Stars Siberian Cranes Sanctuary	7
Other locations	12

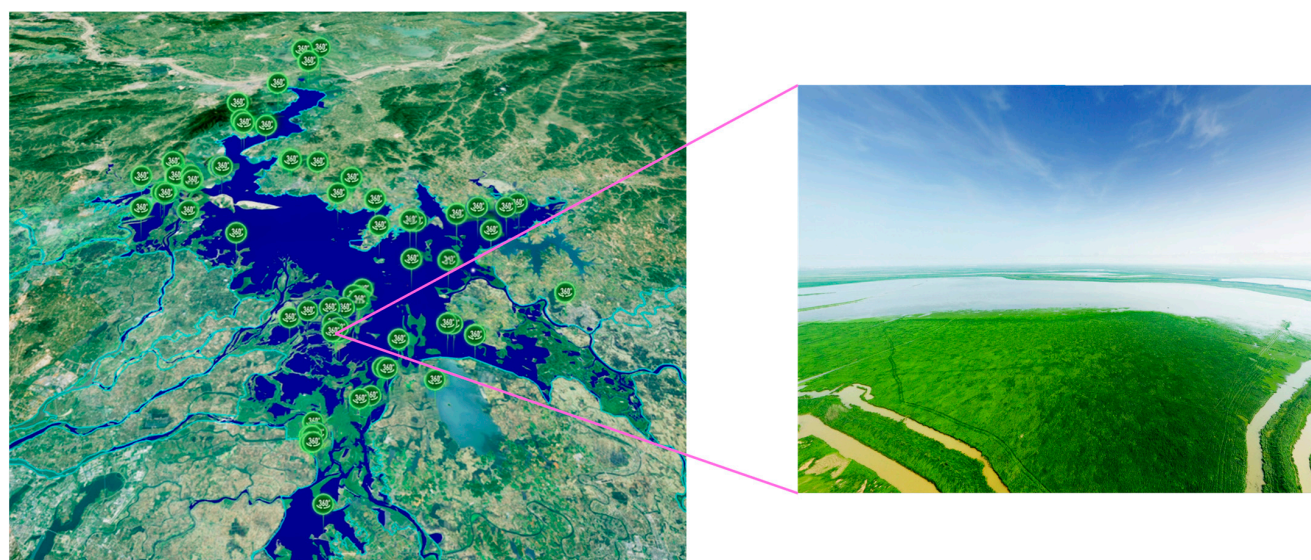


Figure 4. Panoramic wetland landscape distribution in the VE.

L3 denoted a reconstructed virtual wetland environment, including fine model details and dynamic scene change effects. Due to the difficulties related to data collection, storage, and the operation of the 3D reconstruction of landscape types in the whole Poyang Lake area, 28 sites in the Poyang Lake area were selected for virtual reconstruction, as shown in Figure 5. The selected sites were randomly distributed in the six major protected areas.

These sites included typical wetland landscapes and artificial landscapes, such as butterfly lakes, mudflats, grassy continents, and islands in the lake, which could represent and show the whole wetland environment to a certain extent. To integrate the construction of a simulated wetland virtual scene, a combination of multiple sources of data and multiple techniques were used to obtain diverse wetland landscape features, as shown in Figure 6. The terrain of some landscape locations was finely modeled, and 12 common wetland surface textures were rendered into 3D terrain according to the Blended Texture Real Fit rule to increase the realism of a virtual scene [39]. The 3D modeling techniques were used to construct a wetland vegetation model and a building model, as well as to simulate the wind effects on the vegetation. A wetland water material with optical and interactive effects was created using the material blueprint technique. Further, animation techniques were used to create a variety of lightweight gesture-action animations of migratory birds. A variety of weather patterns were created using a particle system to match the real-time weather, and loaded into a virtual scene. A variety of wetland landscape scenarios and simulations of dynamic changes of wetland elements, such as vegetation growth changes in four seasons, water level changes, migratory bird activities, and real-time weather changes, were integrated and constructed.

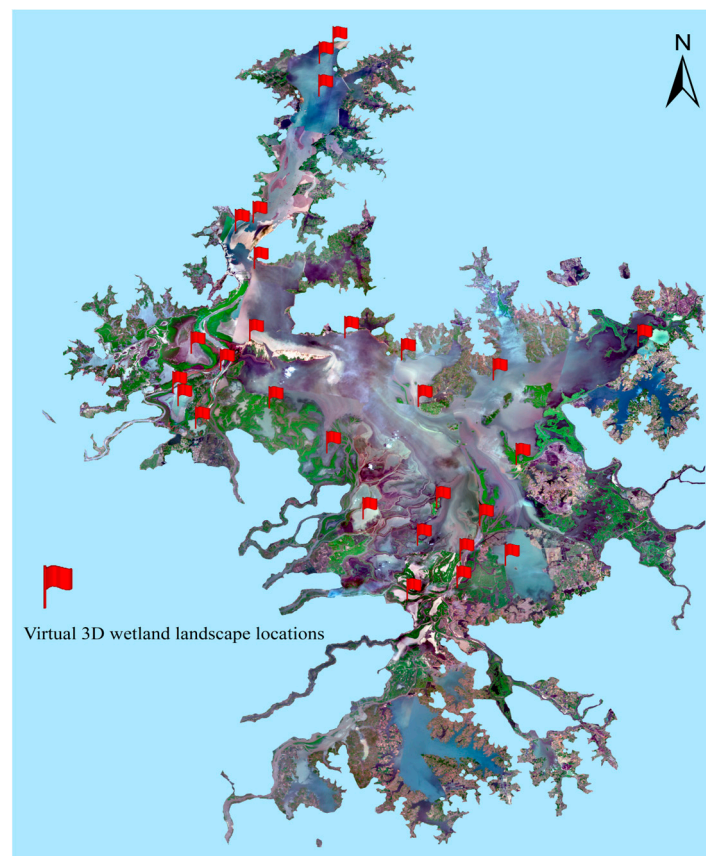


Figure 5. Spatial distribution of selected sites in typical wetland landscapes.

In the virtual scene at L3, diverse models of wetland components, the simulation of dynamic changes in wetland ecological processes, and the simulation of wetland environment perception were included. Therefore, multiscale technology that has been widely used in related research was adopted. First, the triangular mesh on the surface of the constructed model was compressed using Nanite technology for 3D models, which provided a high-resolution presentation of the model details without consuming too much memory [40]. To optimize the dynamic scene and reduce the rendering load, a hierarchical model of detail was used for the scene, where an appropriate level of model detail was dynamically selected based on the distance of the object from the observer's viewpoint. Second, the

lighting was constantly changing in the dynamic scene, and the Lumen global lighting and distance field technology was employed in the game engine to enable real-time ray tracing to simulate high-quality lighting and shadow effects [41]. In addition, following the principle of line-of-sight culling, only objects within the observer's line-of-sight were rendered in a wide scene, thus reducing the rendering time of out-of-sight scenes and models and effectively improving the rendering efficiency and system responsiveness.



Figure 6. The virtual scene with typical wetland landscape features in L3.

4.3. Space Navigation Tasks in MSVE

Multiscale spatial navigation tasks denoted tasks that involved navigating in different scales of space and considered spatial information and geographical features at different scales [42]. Humans use different cognitive strategies in their activities. Therefore, MSVEs with a multilevel hierarchical structure is constructed by integrating different psychospatial cognitive modes, and diversified spatial navigation tasks in the MSVE are accomplished by using different cognitive strategies [43].

First, there was a need to render and present a large amount of geographic information data, including satellite images, models, and dynamic effects. These basic data and shapes provided the basis for spatial navigation and user cognitive patterns about geographic features [44]. Based on the advantages of the hierarchical structure and multiscale technology, the levels focused on a user's viewpoint were prioritized to present the corresponding spatial information and ensure rendering efficiency. The model detail was dynamically adjusted according to the distance between the user's viewpoint and the 3D model to ensure an optimal detailed accuracy of the model nearby.

Second, in the multiscale spatial navigation tasks, it was necessary to consider navigation strategies and methods for different scales [45]. Different spatial scales of each level required using adaptive navigation speeds for the excursion. Users could freely control the navigation speed and perspective shift with the help of external assistive devices (e.g., mouse and keyboard), which ensured a smooth and natural transition between the levels. As the user's viewpoint progressed through the levels, the model details, spatial information, and user perception gradually increased to meet the user's needs from the wetland scope to the specific wetland landscape perception. Allocentric navigation is commonly used in geographical and environmental spaces that are relatively large in relation to the

human body, and egocentric navigation strategies are commonly used in vista and figural spaces that are as large or small as the human body [42]. At the same time, the levels can be articulated and interconnected, and additional navigational strategies have been incorporated into the design, which are categorized as follows: From L0 to L1, users could rapidly select the target wetland reserve according to the information guide or reserve range. From L1 to L2, users could search for wetland landscapes of interest through the point query and semantic query (i.e., wetland landscape type information). From L2 to L3, the 3DVEs with typical wetland landscapes were combined using the goal-based spatial navigation method, so that users could select the location based on their needs and interest targets. In addition, users could select locations according to their needs and interests. Further, in a specific virtual scenario in L3, a variety of VR experience modalities were designed to support the users' spatial navigation and free roaming in the immersive virtual wetland environment to satisfy the users' cognitive needs of the wetland landscape, as shown in Figure 7. Examples presented in Figure 7 included: web interfaces that support remote access, Figure 7a; Cave Automatic VE (CAVE) that could support semi-immersive experiences for multiple users at the same time, Figure 7b; highly immersive head-mounted VR devices (Pico Neo 3), Figure 7c; operator interfaces that were optimized for mobile devices, Figure 7d. The combination of multiple navigation strategies allowed users to be more flexible and efficient in the VEs.

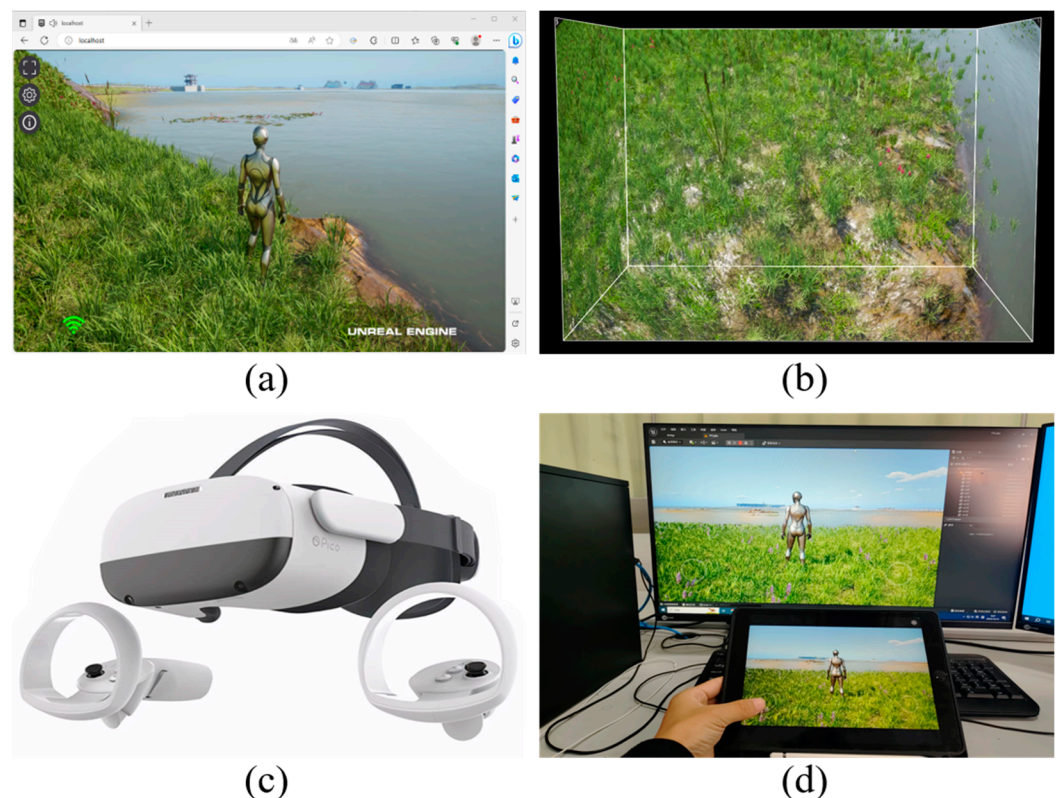


Figure 7. Multiple ways of experiencing VR devices. (a) Virtual experience by web interface. (b) Virtual experience by CAVE. (c) Virtual experience by Pico Neo 3. (d) Virtual experience by mobile device.

Third, performing multiscale spatial navigation tasks also required fault tolerance while ensuring accuracy. The development of the hierarchy-based multiscale virtual wetland environment project for Poyang Lake, in conjunction with the HTML5 web framework, could not only achieve an enhanced functionality and 3D display but also optimize the interactions on the user interface and the spatial information prompts [46]. The MSVE results were successfully integrated into the Poyang Lake Wetland Ecosystem Monitoring and Early Warning Platform and deployed in the Key Laboratory of Poyang Lake Wet-

land and Watershed Research, Ministry of Education, Jiangxi Normal University. In this study, the system was subjected to in-depth testing and fine-tuning to ensure that it could exhibit robustness and high reliability in practical applications. Meanwhile, 17 virtual wetland landscape hotspots with a high user preference were successfully mapped and presented through the statistics and analysis of the user navigation behavior data in the system, as shown in Figure 8. After testing, the adopted hierarchical structure showed good compatibility and stability, confirming that the system ran smoothly and without any obstruction.

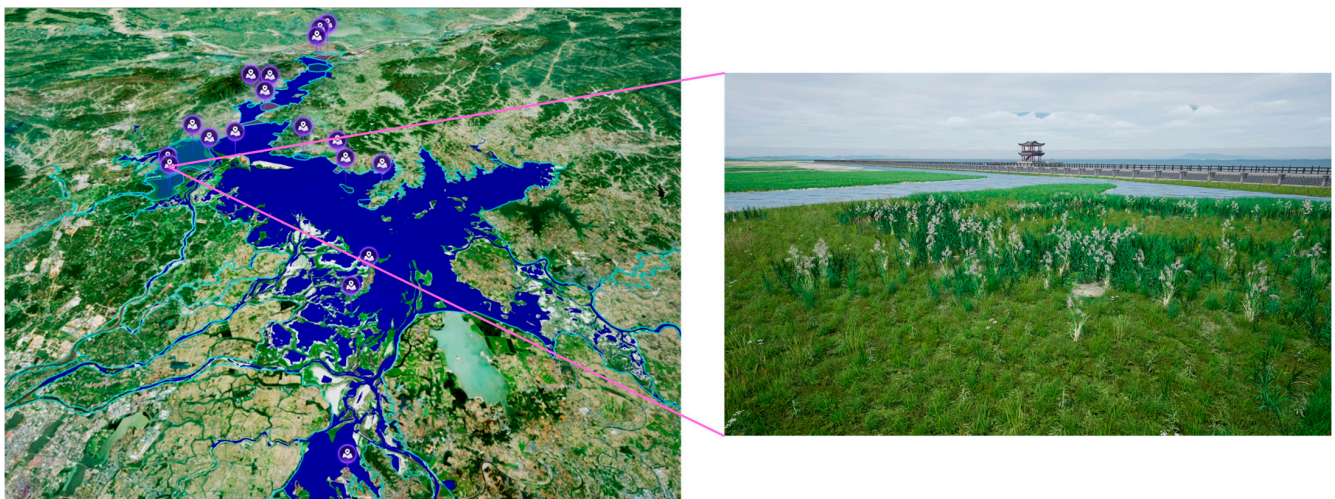


Figure 8. The MSVE spatial navigation integration experiment.

5. Discussion

5.1. MSVE Construction Requirements

An MSVE is a complex and delicate project that requires the in-depth consideration of the hierarchical division, details about the information that needs to be presented at each level, and the data integration and interactivity of the entire VE. Therefore, a multi-level hierarchical approach is required to effectively create an MSVE that combines information richness and a realistic simulation.

A hierarchical structure, with its clear hierarchical rules and logical coherence, can effectively divide and integrate information of different scales in an orderly manner. Different from previous studies [19], this study constructs a multiscale virtual wetland environment with four levels, as described in Section 3.2, considering the characteristics of a natural environment of wetlands and combining the logic of the hierarchical structure and characteristics of different psychological spaces. The four levels correspond to different levels in the hierarchy, having specific geospatial information and covering different scales from macro to micro. Such a VE can provide users with a richer and more detailed virtual experience. Namely, users can engage in experiences according to their needs and interests, from the overall spatial pattern of the wetland to the landscape types, and gradually obtain a deeper understanding and experience of a virtual wetland scene. In a hierarchical structure, the number of levels and layering rules are not fixed, and this type of structure is highly scalable and can support diverse application scenarios. Moreover, it can be flexibly configured and adjusted according to the hierarchical needs of different research objects to meet virtual scenes of various scales and complexities.

Therefore, constructing MSVE requires adopting a multi-level layered hierarchy.

5.2. Promising Applicability of Hierarchical Structure with Spatial and Hierarchical Differences in MSVE

The fusion presentation of data and spatial information at different scales denotes an important challenge in constructing an MSVE. Hierarchical structure, as an organizational

structure, provides a regular path from the large to small scale for the systematic knowledge and understanding of a wetland environment. A hierarchical structure also shows excellent performance in presenting information in an MSVE, constructing an MSVE by integrating different scales of information and gradually presenting more detailed information according to the combination of perspectives and hierarchies.

Observations of a scene from higher viewpoints provide a global spatial understanding but, often, at the cost of insights into local details. By gradually lowering the observation angle, detailed features of the wetland landscape can be slowly revealed. Using hierarchical progression not only can help to deepen the user's spatial perception of the geographic location but can also promote the in-depth reasoning about spatial relationships. This study constructs a multiscale virtual wetland environment based on hierarchical structure and psychological spaces, which enables users to navigate and explore different levels, thus constructing a cognitive framework of the VE at both the global and local levels, enhancing the spatial cognitive ability and depth of understanding. Compared to the previous studies [32], this study addresses the challenge of differences between spaces and levels, such as the similarity in spatial scales at different levels (e.g., waterscapes) and differences in spatial scales at the same level (e.g., localized microtopographic changes). First, for waterscapes with different levels but similar spatial scales, the division rules of psychological spaces and the display function of each level need to be clearly defined. This division principle allows similar spatial scales to be displayed on different levels, and higher levels usually display larger amounts of information. In addition, the hierarchical display functions are designed to ensure that content at a particular level is presented only when the viewpoint is at that level. Second, when constructing a refined model for localized microtopographic changes in wetlands at the same level but at different spatial scales, it is necessary to adjust the level of detail of the model dynamically according to the distance between a user's viewpoint and the terrain. Finally, implementing a multi-strategy spatial navigation model in a multi-level hierarchical structure can provide an effective presentation of the content to a user.

Therefore, hierarchical structures show a strong applicability in dealing with spatial and hierarchical differences in MSVEs.

5.3. User Experience Improvement Using Multiple Spatial Navigation Strategies in MSVE

Spatial navigation tasks are an important part of VR technology, enabling users to effectively orient and navigate in VR. However, traditional spatial navigation models often ignore the subjective cognitive laws of users, resulting in a poor user experience [17]. Using a perspective shift approach based on the spatial hierarchical progression is an effective method to match human spatial cognitive habits better. Combining user perspective and spatial cognition can help users understand and perceive spatial information more clearly, which is of great significance to the study of spatial navigation in VR [47]. To this end, this paper proposes a hierarchy-based spatial navigation method, which can effectively conform to the laws of human spatial cognition through the coupling of a user's progressive perspective shift and spatial cognition.

In this study, four levels are defined to integrate multiple spatial navigation strategies using the hierarchical structure of an MSVE to optimize navigation efficiency. Level L0 is used to present the morphology and spatial pattern of the wetland, and its spatial navigation task and strategy adopt fast positioning with an adaptive navigation speed on a large scale. Level L1 is implemented to present the partition of protected areas within the wetland, and its spatial navigation task and strategy tend to navigate through the goal information on a medium scale. Level L2 is employed to present wetland landscape types, and its spatial navigation task and strategy are semantic querying and indexing at small scales. Finally, level L3 is used to present virtual wetland scene changes at micro scales, and its spatial navigation task and strategy denote free roaming with map guiding and user perspective manipulation. The method of the gradual transformation of the user perspective with spatial levels through the MSVE can satisfy users' spatial cognitive transformation

from the region to the wetland landscape. In addition, a variety of navigation strategy approaches are embedded in different levels, and users can select the most appropriate navigation strategy according to their needs, thus enhancing their virtual experience.

Therefore, multiple spatial navigation tasks and strategies in the MSVE can improve the user experience.

6. Conclusions

This research introduces the MSVE design and interactive spatial navigation based on a hierarchical structure and psychological spaces, which can effectively satisfy users' spatial cognition of MSVEs by integrating the mechanism of the gradual transformation of users' viewpoints and the theory of spatial cognition. The adopted strategy aims to improve the MSVE construction and optimize the design of virtual navigation systems to enhance users' navigation intuition and ease of operation, promoting their spatial comprehension and exploration skills in simulated environments. A wetland of Poyang Lake is selected as an experimental area, and a wetland VE with four scales is constructed. A spatial navigation strategy that progresses with the user's perspective is designed. The VEs are integrated into the Poyang Lake Wetland Ecosystem Monitoring and Early Warning Platform, and a variety of navigation strategies are integrated to meet the needs of more users navigating in the VE and released to the Key Laboratory of Poyang Lake Wetland and Watershed Research, Ministry of Education, Jiangxi Normal University. The experimental results show that the proposed hierarchy-based approach can effectively construct an MSVE, and that different content effects are evident at different scale levels. The method of the gradual transformation of the user perspective coupled with spatial hierarchy can effectively meet the law of human spatial cognition; the combination of multiple strategies can satisfy the user's navigation experience in VEs. Moreover, the hierarchical design approach shows a high scalability and stability and the ability to support diverse application scenarios.

Despite the promising results achieved in this study, there are still certain limitations that need to be addressed in future work. First, for unfamiliar users, relying on incremental changes in perspective can help to acquire a certain amount of spatial knowledge but cannot reliably create comprehensive spatial cognition. Nevertheless, a certain amount of a priori empirical knowledge can serve as a basis. Thus, the further refinement of the information cue function in an MSVE is required. Second, the proposed method considers the variations in spatial hierarchical scales about a user's spatial cognition but does not provide an immersive route navigation function in 3DVEs. Therefore, future work could enrich the immersive spatial route navigation based on location position. Thirdly, this study is currently limited to the consideration of place name attribute information when constructing the VE. However, to pursue a more detailed and comprehensive simulated environment, there is an urgent need for richer attribute data, including key ecological information, such as wetland vegetation types and migratory bird species.

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