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EXPLORING THE DUAL ROLE OF ECOLOGICAL LANDSCAPES IN THE RHINE BASIN FOR SPATIAL MEMORY AND SUSTAINABLE DEVELOPMENT

Abstract: As an important natural and cultural landscape in Europe, the Rhine basin is both an expression of ecological values and an important carrier of cultural memory. However, with increasing urbanisation and globalisation, its local landscapes and ecosystems are under threat. This study focuses on exploring the dual role of local landscapes in spatial memory and sustainable development. Through visual landscape analysis, cultural narrative coding, *VR* modelling and questionnaire survey, the study found that the visual attractiveness and cultural significance of ecological landscapes can significantly enhance spatial memory, and that *VR* technology can increase public awareness and participation in conservation through immersive experiences. By employing Carbon Sink Capacity Analysis Model and Water Resource Regulation Model, this study found that the area around the cultural landmarks is particularly strong in terms of carbon sinks, water regulation and other ecological functions. This study provides a new theoretical framework and practical way forward for landscape conservation and ecological education.

Keywords: ecological landscape, virtual reality, sustainable development, spatial memory, Rhine basin

Introduction

Located in the heart of Europe, the Rhine River Basin is an important part of the world's heritage with its unique natural landscapes and deep cultural heritage [1]. The ancient castles, medieval towns and vineyard terraces along the banks of the river not only bear witness to the historical changes of the region, but also shape the unique local cultural memory. These local landscapes not only carry cultural significance, but also play important roles in the ecosystem, such as water resource regulation, biodiversity conservation and climate regulation. In recent years, however, the local landscapes and ecological functions of the Rhine basin have been under increasing threat because of urbanisation, tourism development and climate change.

Endemic landscapes are the product of the intersection of culture and nature. As visual and cultural symbols, they occupy an important place in spatial memory through their significant visual characteristics and rich cultural narratives. Spatial memory is not only the embodiment of sense of place, but also the link between people and the environment. However, these landscapes are gradually being weakened in the process of globalisation, and their uniqueness and local values need to be preserved and inherited. At the same time, the degradation of local landscapes not only threatens the sustainability of regional

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ecosystems but may also lead to the loss of cultural heritage values, which may negatively affect the sense of identity and cultural pride of communities [2].

Currently in academia and practice, research on landscape conservation is gradually developing in a multidimensional and interdisciplinary direction. Ecological landscapes and cultural narratives are two indispensable dimensions in landscape conservation: the former embodies the ecological service value of nature, and the latter endows landscapes with unique historical and cultural significance. Studies have shown that combining ecological landscapes with cultural narratives not only helps to enhance the comprehensive benefits of landscape conservation, but also better supports the sustainable development of the region. However, how to quantify and assess the ecological and cultural values of landscape symbols remains an urgent challenge.

In this context, Virtual Reality (*VR*) technology, with its immersion and interactivity, offers new possibilities for the conservation and dissemination of local landscapes. Through *VR* technology, endangered ecological landscapes and cultural memory scenes can be recreated to provide immersive experiences for the public, stimulate their conservation awareness and promote community participation. At the same time, *VR* technology can also be used as a research tool to help analyse the impact of visual and cultural symbols on spatial memory. For example, immersive *VR* experiences can enhance the public's memory and emotional connection to local landscape symbols by recreating historical landscapes, thus strengthening their awareness of ecological and cultural conservation [3].

However, the current research on *VR* technology in landscape conservation still has some limitations. On the one hand, most of the studies focus on the digital preservation of cultural heritage and pay insufficient attention to the combination of ecological landscapes and cultural narratives; on the other hand, the application of *VR* technology is mostly focused on the display and dissemination level, and the exploration of its potential in public education and behavioural change is still not deep enough. Therefore, combining *VR* technology with ecological landscapes and cultural narratives to construct a set of multi-dimensional conservation and communication framework is an important direction to achieve sustainable landscape development [4].

This study aims to explore the dual role of local landscapes in the Rhine River Basin for spatial memory and sustainable development, with a specific focus on the following core questions:

1. how do ecological landscapes become an important component of spatial memory through their visual appeal?
2. how do cultural narratives enhance the emotional value of landscape symbols and facilitate their transmission?
3. what is the potential of landscape landmarks in carbon sinks, water regulation and other ecological functions?

By integrating visual landscape analysis, cultural narrative coding and *VR* experimental design, this study attempts to construct a set of multi-dimensional research frameworks to provide theoretical support and practical paths for the conservation and ecological sustainable development of local landscapes. Figure 1 shows the conceptual framework of this study.

This study has important academic value and practical significance: at the theoretical level, it deepens the understanding of the relationship between ecological landscapes, cultural narratives and spatial memory; at the practical level, it explores the innovative application of *VR* technology in landscape conservation and provides new methods and ideas for the sustainable development of the region. This study not only provides a reference for cultural and ecological conservation in the Rhine River Basin, but also has implications for the conservation of other similar cultural landscape regions.

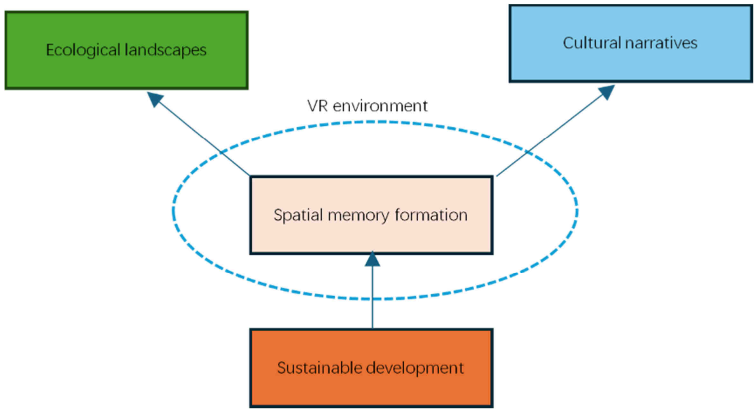


Fig. 1. Conceptual framework: interaction of landscapes, narratives and *VR*

Literature review

Ecological landscapes

Ecological landscapes, which are the result of the joint action of natural processes and human activities, have a rich connotation as a cross-cutting concept of geography, ecology and environmental science. In terms of the definition, characteristics, constituent elements and their ecological and social significance of ecological landscapes, research in this field not only reveals the complexity of ecosystem functioning, but also emphasises the dynamic relationship between human activities and natural processes.

An ecological landscape can be defined as a spatial area consisting of multiple ecosystems that are interconnected through material, energy, and information flows to form a whole with a certain structure and function [5]. This concept was further expanded by Turner [6], who argued that ecological landscapes are composed of a combination of natural and human-dominated patches, corridors, and substrates, and are regional units with significant spatial heterogeneity. Its morphology is influenced by both natural geographical processes and human activities. The types of ecological landscapes include undisturbed natural landscapes (e.g. forests, wetlands) and human activity-dominated agricultural landscapes, urban landscapes, etc., and their comprehensive perspectives reflect the dynamics and diversity of ecological landscapes.

The core characteristics of ecological landscapes are expressed in three aspects. The first is spatial heterogeneity, which means that there are significant differences in the morphology, function and spatial distribution of different ecological patches. Patches, corridors and substrates are the basic structural units of ecological landscapes [7], for example, in the Rhine River Basin, rivers, forests, terraces and towns are intertwined, constituting a typical heterogeneous landscape. Second is dynamism, where ecological landscapes are continuously changing on time scales, driven by factors such as climate change, natural disasters and human activities [8]. The wetland landscape of the Rhine is constantly adapting its structure and function in response to changes in flood frequency and intensity. Finally, there is hierarchy, where ecological landscapes can exhibit a diversity of ecological processes at different spatial scales between localised (e.g. a forest) to regional (e.g. an entire watershed) [9].

Among the components of ecological landscapes, natural and anthropogenic elements work together to determine their structure and function. Natural elements include topography, hydrology and biodiversity, of which the topography serves as the physical basis and determines the overall pattern of the ecological landscape; the hydrological system provides habitat and ecological regulation; and plant communities and animal populations form the biological basis of the ecological landscape. The anthropogenic elements are mainly represented by land use patterns and cultural landscape symbols, such as medieval castles and vineyard terraces, which are not only an important part of the cultural memory but also play a unique role in ecosystem services. Ecological landscape is important in ecosystem services. It can provide supporting services (e.g. soil formation and gene pool), regulating services (e.g. climate regulation and flood control) and cultural services (e.g. aesthetic enjoyment and spiritual significance) [10-12]. The connectivity of ecological landscapes enhances the potential for species migration and gene exchange through corridors (e.g., rivers and forest belts) [13], while their diversity and heterogeneity make them more resilient and enable them to restore ecological balance after disturbance [14].

Ecological value of ecological landscape

As a collection of multiple ecosystems, the ecological value of ecological landscapes is mainly reflected in the function of ecosystem services. Ecosystem services can be categorised into four main groups: support services, regulation services, provisioning services and cultural services [11, 15]. Together, these services maintain the balance of the ecosystem and provide multiple levels of value to human society. The ecological value of ecological landscapes lies not only in the material resources they provide, but also in their role in regulating the environment and enhancing social and cultural identity.

Firstly, support services are the basic functions of ecological landscape operation, including soil formation, nutrient cycling and biodiversity maintenance. For example, the forests and wetlands of the Rhine basin provide the necessary support for the healthy functioning of the ecosystem through soil formation and nutrient cycling [16]. These processes maintain the conditions for the region’s flora and fauna through organic matter decomposition and nutrient recirculation. At the same time, the ecological landscape is an important carrier of biodiversity [17]. The wetlands and woodlands of the Rhine Basin not only provide habitat for native flora and fauna, but also provide critical support for the conservation of endangered species, further highlighting the importance of support services.

Secondly, regulating services play an integral role in the ecological value of the ecological landscape. This includes functions such as climate regulation, water regulation and pollution control. For example, forests in the Rhine basin act as carbon sinks in global climate regulation by absorbing carbon dioxide through photosynthesis. At the same time, wetland landscapes play an important function in regional hydrological regulation, such as mitigating flood threats and improving water quality. The filtering effect of vegetation also effectively reduces water pollution from agricultural and urban activities, ensuring the sustainable use of water resources [18]. These regulatory functions are important for maintaining ecological balance and protecting human health.

Once again, ecological landscapes provide direct material resources for human beings through the provision of services. The agricultural landscape of the Rhine basin, especially the vineyard terraces, produces high-quality wines that not only fulfil the demand for food, but also serve as a symbol of regional culture [19]. In addition, the ecological landscape provides mankind with fresh water resources. The Rhine and its wetlands provide drinking and irrigation water for the people living along its banks through water circulation and filtration functions. At the same time, the forested landscape of the basin provides sustainably harvested timber resources for the construction industry and furniture manufacturing. These provisioning services not only support regional economic development, but also provide economic incentives for landscape conservation [20].

Cultural services are another important expression of the ecological value of ecological landscapes, which provide non-material values to human society through aesthetics, recreation and spiritual significance. The landscapes of the Rhine basin have become symbols of European Romanticism due to their unique aesthetic value [21]. The Lorelei Rock, for example, not only enhances the sense of place but also attracts large numbers of tourists due to its cultural narrative associated with the legend. The recreational function of ecological landscapes should not be overlooked. Hiking, eco-tourism and cultural festivals in the Rhine Valley not only provide the public with opportunities to interact with nature, but also serve as an important way to raise awareness of environmental protection [22]. In addition, as a natural laboratory, the ecological landscape provides an important platform for environmental education and scientific research [23].

The threat of landscape degradation

Landscape degradation is a major challenge facing natural and cultural landscapes on a global scale. The ecological functions and cultural values of landscapes are increasingly threatened by the multiple impacts of climate change, urbanisation and expansion, irrational land use and human activities. Such degradation not only destroys ecosystem services, but may also lead to the loss of cultural memory, posing a serious threat to the sustainable development of the region.

First, climate change is one of the main drivers of landscape degradation. Global warming has led to a high incidence of extreme climatic events, such as droughts, floods and heat waves, which pose a direct threat to the ecosystem functions of natural landscapes [24]. For example, wetland and river ecosystems in the Rhine River Basin are under serious threat due to climate change-induced abnormalities in the hydrological cycle. The increased frequency and intensity of floods not only destroys the vegetation along the rivers, but also affects the biodiversity of the region [25]. In addition, warmer temperatures are negatively affecting vegetation cover and forest health, further weakening the climate regulation function of the landscape.

Secondly, rapid expansion of urbanisation is another major cause of landscape degradation. Globally, the growth of urban areas is usually accompanied by the reduction and fragmentation of natural landscapes [26]. Some areas of the Rhine basin have lost significant agricultural land and wetland ecosystems to urban expansion. Urbanisation processes not only lead to a decrease in the spatial heterogeneity of the landscape, but also exacerbate the loss of ecological connectivity [27, 28]. The destruction of corridors impedes species migration and gene exchange, making ecosystem resilience significantly weaker. In addition, urban expansion has brought about problems such as heat island effect, air pollution and water quality deterioration, further threatening the ecological function of the landscape.

Again, irrational land use and agricultural expansion have accelerated the process of landscape degradation [29, 30]. In pursuit of short-term economic benefits, large-scale agricultural activities and over-exploitation often lead to soil erosion, water resource depletion and habitat loss. For example, although terraced agriculture in the Rhine basin has traditional cultural values, improper management and the use of chemical pesticides may trigger land degradation and water pollution [31]. In addition, overgrazing and deforestation cause irreversible damage to soil fertility and ecological balance.

Tourism development triggered by human activities also poses a potential threat to the sustainability of the landscape [32]. Although ecotourism provides important support to local economies, excessive numbers of tourists and poor management can put pressure on sensitive natural and cultural landscapes [33]. For example, in the Rhine basin, some famous landscapes such as the Lorelei Rock and medieval castles face landscape destruction and dilution of cultural significance due to overexploitation. The burden of large numbers of tourists on natural ecosystems and cultural heritage not only reduces their aesthetic and educational value, but also threatens to upset the original ecological balance [33]. For example, in the Rhine basin, some famous landscapes such as the Lorelei Rock and medieval castles face landscape destruction and dilution of cultural significance due to overexploitation. The burden of large numbers of tourists on natural ecosystems and cultural heritage not only reduces their aesthetic and educational value, but also threatens to upset the original ecological balance.

Interaction between ecological landscapes and cultural narratives

There is a profound interactive relationship between ecological landscapes and cultural narratives, which together shape the ecological function and cultural significance of local landscapes [34]. This interactive relationship is reflected in the fact that ecological landscapes provide material carriers for cultural narratives, while cultural narratives enrich the connotation of ecological landscapes through emotional empowerment and historical contexts, thus realising the synergistic gain of natural and cultural values [35, 36].

Firstly, ecological landscapes provide a material basis for cultural narratives. The natural characteristics of the landscape, such as topography, vegetation, hydrology, etc., constitute the core carrier of cultural narratives. Landscape elements with high visual salience (e.g. rivers, mountains and rocks, ancient trees) often become the starting point and symbolic object of narratives. For example, the Lorelei Rock of the Rhine becomes a central symbol of the cultural narrative due to its unique geological form and geographical location, which further enhances its cultural significance and makes it transcend the physical attributes of the natural landscape to become an important symbol of Romantic culture [37]. This combination of nature and culture makes the landscape not only ecologically valuable, but also a key carrier of the sense of place [38].

Secondly, cultural narratives strengthen the social value of ecological landscapes through emotional empowerment and meaning construction. Cultural narratives endow landscapes with historical, cultural and emotional dimensions, making them symbols of local memory and collective identity, and Nora suggests that ‘places of memory’ are specific landscape symbols formed through cultural narratives, representing the collective memory of communities or peoples. For example, medieval castles in the Rhine Valley are not only culturally valuable because of their military history, but also as vehicles for cultural narratives through literary and artistic creations (e.g. Romantic poetry) [39]. These narratives reinforce the public's emotional connection to the ecological landscape, thus enhancing public participation and sustainability of landscape conservation.

Again, the interactive relationship between ecological landscapes and cultural narratives is reflected in the co-shaping of regional spatial structure and cultural significance. The spatial distribution of ecological landscapes is closely related to the transmission network of cultural narratives, and together they influence the social functions and economic values of local landscapes [40, 41]. For example, the vineyard terraces of the Rhine Valley are both an important part of the regional ecosystem and a globally recognised cultural landscape due to the narratives of wine culture. The ecological functions of the vineyards (e.g., preventing soil erosion, maintaining biodiversity) and the cultural significance (e.g., wine festivals, agricultural traditions) reinforce each other, and together they enhance the region's tourism appeal and economic value. This ecological and cultural synergy provides important support for landscape conservation and regional development [42].

In addition, the conservation of ecological landscapes is also dependent on the dissemination of cultural narratives and the enhancement of public awareness. Cultural narratives raise public awareness of the importance of landscape conservation by recounting the historical and cultural values of the landscape [43]. For example, by combining the Rhine Castle with historical events and literature, cultural narratives can raise public awareness of conservation and motivate local governments and communities to participate. The restoration of ecological landscapes (e.g. wetland restoration, revegetation) can be supported through cultural narratives, thus achieving the joint protection of natural and cultural heritage.

Finally, the interaction between ecological landscapes and cultural narratives also has a profound impact on the sustainable development of the region. Giving meaning to ecological landscapes through cultural narratives not only enhances public environmental awareness, but also promotes local economic development. Eco-tourism, educational activities and cultural festivals are typical examples of this interaction. For example, the development of tourism programmes in the Rhine basin that are linked to nature and cultural narratives not only attracts tourists, but also focuses on ecological protection in the economic returns, thus achieving synergistic development of culture and ecology.

The role of *VR* technology in spatial memory and landscape research

Virtual reality technology, with its immersion, interactivity and multi-sensory stimulation, has demonstrated significant application value in spatial memory and landscape research in recent years. Pine and Gilmore's [44] Experience Economy Theory emphasises that emotion and experience are the core drivers of memory, and *VR* technology enhances users' spatial memory depth through highly immersive virtual scenes and multisensory interaction enhances the depth of users' memory of the space. Through integrated visual, auditory, and tactile stimulation, *VR* provides users with a depth of experience that goes beyond traditional media, resulting in a more lasting and delicate spatial memory.

In terms of landscape research, Champion points out that *VR* technology, through the digital reconstruction of historical and cultural landscapes, not only effectively preserves endangered cultural heritage, but also provides the public and researchers with new interactive ways of exploration [45]. For example, landscapes such as ancient castles and vineyards in the Rhine Valley can be highly recreated through *VR* technology, allowing users to gain immersive experience without having to visit the site [46]. This virtual environment breaks through the geographical and time constraints of traditional experiences, expands the scope and influence of cultural heritage dissemination, and at the same time enhances public awareness of conservation [47].

The dynamic simulation function of *VR* technology in ecological landscape research has also been paid attention to by scholars, and Forman's theory of landscape ecology shows that dynamic simulation technology can help researchers observe the changes of ecosystems and the impacts of human activities intuitively [7]. By simulating the ecological changes in the Rhine River Basin through virtual environments, researchers can better assess the long-term impacts of climate change and human interventions on the regional ecology, and provide a scientific basis for ecological conservation and landscape management.

The visualisation and interactive presentation of cultural narratives is another major contribution of *VR* technology in landscape research: Huyssen's theory [48] of the geography of memory states that the formation of memories is closely related to spatial and social contexts, and that *VR*, through the recreation of virtual scenarios, provides users with a 'place of memory' that transcends time and space, making cultural narratives more accessible [48]. *VR* provides users with a 'place of memory' across time and space through the reproduction of virtual scenes, allowing cultural narratives to be transmitted more intuitively and emotionally [49]. By exploring and interacting in the virtual environment, users can trigger multidimensional perceptions of historical events or cultural symbols, thus deepening their identification with the cultural landscape [50].

In addition, multisensory theory further explains the mechanism of *VR* technology in memory enhancement; Pallasmaa suggests that spatial experience not only relies on vision, but also involves auditory, tactile, and kinesthetic perceptions, and that by integrating multisensory experiences, *VR* technology provides more memory cues, thus enabling spatial memory to be enhanced [51]. *VR* technology provides more memory cues by integrating multi-sensory experiences, thus making spatial memory more three-dimensional and vivid [52]. Compared with traditional media, *VR* technology can provide a concrete and highly immersive virtual scene during the process of memory encoding and extraction, helping users to understand and remember landscape information more comprehensively [53].

However, the application of *VR* technology also faces some challenges. Champion points out that the authenticity of the virtual scene relies to a certain extent on the developer's choices, which may lead to biased cultural narratives or incomplete landscape information. In addition, technological thresholds and high costs limit the widespread adoption of *VR* technology in non-developed regions or small research organisations [45]. Nonetheless, as *VR* combines with augmented reality (AR) and mixed reality (MR) technologies, its potential in landscape research and cultural communication remains vast.

Research methodology

Methodological framework

To illustrate the methodology of this study, a methodological framework (Fig. 2) is presented to show how different data types (cultural, visual, ecological) are analysed and integrated into *VR* scene modelling. It also maps how these elements lead to key research outputs like user experience evaluation, memory and attitude assessment, and sustainability insights.

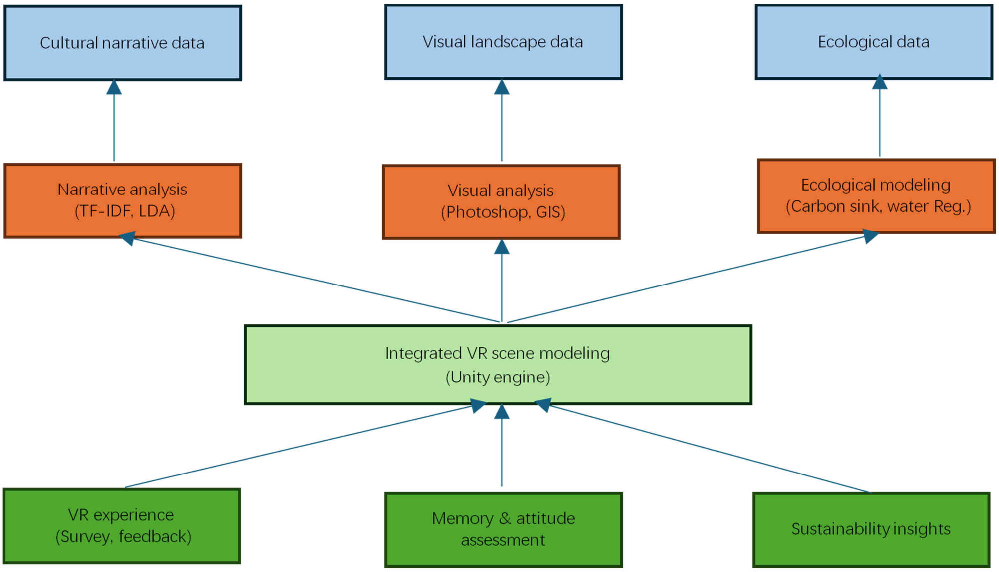


Fig. 2. Methodological framework for *VR*-enhanced landscape research

Data collection

Cultural narrative data

Table 1

Examples of the cultural narrative data

Source type	Sample excerpt	Narrative theme
Historical document	"In the year 1324, the fortress above Oberwesel was expanded to defend against incursions from the west. Its towers stood as both military bastions and symbols of feudal power."	Fortress evolution, medieval defense
Literary work	*"She combs her golden hair / And sings a song so fine, / It carries a spell on the evening air / A magic from the Rhine."* (adapted from Heinrich Heine's *Lorelei*)	Romanticism, enchantment, poetic imagery
Local legend	"The old winemakers say that when the fog rises over the vineyards, you can hear the Lorelei's voice echoing down the cliffs. They believe she protects the harvest."	Lorelei myth, vineyard symbolism
Oral history (interview)	"My grandfather told me the castle ruins used to glow at night, not from ghosts, but from the pride people had in their stories - every stone held a memory."	Intergenerational memory, local identity
Regional folklore	"In the festival of the flames, the river is lit in red - people say it mimics the fire from when the castles burned in ancient wars, now turned into celebration."	Historical transformation, cultural ritual

Cultural narrative data enrich the historical and cultural context of the Rhine Valley's landscapes, bridging visual symbols and spatial memory. This study collected narrative data from historical documents, literary works, and local legends. Historical records from archives and regional databases provided insights into the evolution of fortresses, feudal conflicts, and medieval cultural shifts. Literary works, such as Heinrich Heine's *Lorelei*, highlighted symbolic depictions of the Rhine in 19th-century Romanticism. Local legends, gathered through interviews with residents and experts, documented stories like the Lorelei myth and vineyard traditions, enhancing the *VR* scenes with authentic cultural narratives and emotional depth. Table 1 shows some examples of the cultural narrative data collected in this study.

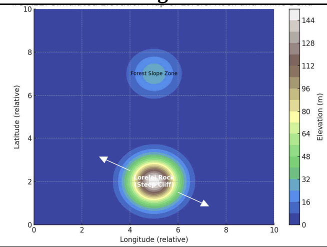
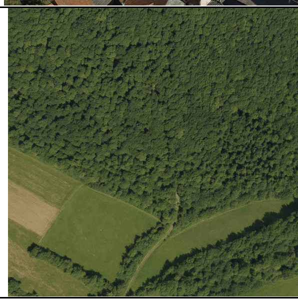
Visual landscape data

Visual landscape data collection was conducted using three main sources: Google Street View, UAV (drone) images, and Geographic Information System (GIS) data. Google Street View provided panoramic images capturing landmark landscapes such as castles, river morphology, and vegetation in the Rhine Valley, which informed virtual path design and 3D scene enrichment. UAV images captured high-resolution details of local landscapes, including castle ruins and vineyards, using photogrammetry to create 3D models from multi-angle aerial shots. GIS data supplied accurate geospatial information, including road networks, river paths, and terrain elevation, obtained from OpenStreetMap, the European Environment Agency (EEA), and Copernicus DEMs to support spatial analysis and landscape modelling. Table 2 presents some examples of the visual landscape data used in this study.

Table 2

Examples of the cultural narrative data

Source	Location	Visual element description	Figure
Google street view	Oberwesel Castle	Panoramic view of the castle façade with aged stone textures, ivy-covered walls, and surrounding forested slope	
UAV (Drone image)	Vineyard Terraces near Bacharach	Terraced slopes with linear vineyard rows, varying shades of green and brown depending on sun and crop cycle	

Source	Location	Visual element description	Figure
GIS elevation data	Lorelei Rock and Rhine bend	Steep cliff edges, vertical topography, and river curvature visible through contour lines	
UAV (oblique aerial)	Medieval Town Center of St. Goar	Dense red-roofed houses clustered near riverbank, cobbled streets, and church spire	
GIS + satellite data	Mixed forest zone (North Rhine slope)	Mixed deciduous and coniferous canopy textures, irregular patch patterns, and seasonal NDVI variation	

Ecological data

Table 3

Examples of ecological data of the Rhine Basin

Data source	Ecological variable	Metric
Sentinel-2 (Copernicus)	Vegetation cover (NDVI Index)	NDVI values ranged from 0.32 (urban edge) to 0.78 (forest canopy) in summer 2023
Sentinel-2 (Copernicus)	Land use classification	Mosaic of vineyards (35 %), mixed forest (28 %), wetlands (12 %), urban (18 %), others (7 %)
BKG (National geographic data centre)	Wetland distribution	Identified key wetlands near Bacharach and Bingen; high water retention areas (> 0.65 rating)
BKG biodiversity habitat maps	Species habitat overlap zones	Rhineland region supports 3 overlapping protected species zones (bat, stork, wild grapevine)
ICPR environmental reports	River water quality index (WQI)	Rhine section near St. Goar rated “Good” (WQI = 78); nitrate levels declining since 2010
ICPR monitoring reports	Climate impact trends	Increased flood frequency (+18 % over 30 years); prolonged low-water periods documented

Ecological data provides a scientific foundation for characterising the Rhine basin’s landscapes, constructing authentic virtual scenarios, and supporting sustainable development strategies. Data was obtained from satellite imagery, eco-geographic databases, and environmental monitoring reports. Sentinel-2 remote sensing data from the

Copernicus programme offered insights into vegetation cover, water dynamics, and land use distribution. The German National Geographic Data Centre (BKG) provided detailed information on wetland distribution, biodiversity habitats, and river hydrology. Additionally, environmental reports from the ICPR documented long-term trends in water quality, pollution control, and ecological restoration, highlighting the impacts of climate change and conservation efforts in the basin. Table 3 presents some examples of the ecological data used in this study.

Techniques

Analysis of visual and cultural narratives

The analysis of visual and cultural narrative data is an important part of this study, aiming to reveal the visual appeal of landscape elements and the emotional significance of cultural narratives. This section of data analysis combines image processing tools and text analysis software to integrate quantitative and qualitative methods. First, visual landscape data is analysed using Photoshop to assess key elements of its visual appeal. This includes a quantitative analysis of visual features such as colour, composition, and contrast. For example, by analysing the visual elements of castles, rivers, and terraces along the Rhine, aesthetic features with symbolic significance are extracted to provide a scientific basis for the modelling of virtual reality scenes.

For the cultural narrative data, text analysis software (NVivo) is used for coding and analysis. Through semantic analysis and theme mining, emotional expressions, historical meanings, and cultural symbols in the narratives are categorised and summarised. To further analyse the emotions and themes within the cultural narratives, we applied *TF-IDF* and the *LDA* (Latent Dirichlet Allocation) topic model. *TF-IDF* is a commonly used text analysis method that helps identify key terms with cultural significance and emotional meaning by evaluating the frequency of terms within a document and their rarity across the entire corpus. The *TF-IDF* calculation involves two main components: term frequency (*TF*) and inverse document frequency (*IDF*). First, *TF* represents how frequently a term appears in a document, calculated as:

$$TF(t,d) = \frac{\text{Number of times term } t \text{ appears in document } d}{\text{Total number of terms in document}}$$

Next, *IDF* represents how rare a term is across the entire corpus, calculated as:

$$IDF(t) = log\left(\frac{N}{df(t)}\right)$$

where N is the total number of documents in the corpus and $df(t)$ is the number of documents containing the term t. When a term appears frequently across multiple documents, its *IDF* value is smaller, and conversely, when a term appears in fewer documents, its *IDF* value is higher. Thus, *IDF* measures the specificity of a term.

Combining *TF* and *IDF*, we get the *TF-IDF* value, which is calculated as:

$$TFIDF(t,d) = TF(t,d) \cdot IDF(t)$$

By calculating the *TF-IDF* value for each term, we can extract the most frequent and significant terms and generate a word cloud. In the word cloud, the size of each term reflects its *TF-IDF* value. Terms with higher frequency or stronger cultural significance appear larger. This visualisation method allows us to see the most emotionally and culturally significant terms in the narrative. Moreover, *TF-IDF* can assist in sentiment analysis by identifying keywords that express the strongest emotions, further enhancing our understanding of the emotional and cultural layers of the narrative.

On the other hand, the *LDA* topic model helps uncover latent topics in the text using a probabilistic generative approach. *LDA* assumes that each document is composed of a mixture of several topics, each of which is represented by a distribution of words. The goal of the *LDA* model is to infer the latent topic distributions from a given set of documents. The generative process of the *LDA* model can be represented by the following formula:

$$P(\theta,\phi,z \mid \alpha,\beta,w) = \prod_{d=1}^{D}\left[\prod_{n=1}^{N_d} P(w_{d,n} \mid \phi_{z_{d,n}})P(z_{d,n} \mid \theta_d)\right] \cdot P(\theta_d \mid \alpha) \cdot P(\phi_k \mid \beta)$$

Here, θ_d represents the topic distribution for document d_t, ϕ_k represents the word distribution for topic $k_r, z_{d,n}$ represents the topic of the n-th word in document d, and $w_{d,n}$ represents the n-th word in document d. *LDA* uses this formula to model the relationship between documents and topics, helping us uncover the core topics within the cultural narratives. Specifically, *LDA* assumes that each document is a mixture of multiple topics, and each topic is represented by a distribution of words. By inferring the distribution of these latent topics, we can uncover the central cultural topics in the text.

During the inference process, we typically use Gibbs sampling or variational inference methods to approximate the topic distributions. The Gibbs sampling update formula is as follows:

$$P(z_{d,n} = k|_{-d,n}, w) \propto \frac{\left(n_{d,k}^{-d,n} + \alpha\right)\left(n_{k,w_{d,n}}^{-d,n} + \beta\right)}{\left(n_k^{-d,n} + W\beta\right)}$$

Here, $n_{d,k}^{-d,n}$ represents the frequency of topic k in document d (excluding the n-th word), $n_{k,w_{d,n}}^{-d,n}$ represents the frequency of word $w_{d,n}$ in topic $k, n_k^{-d,n}$ is the total frequency of all words in topic k (excluding the n-th word), and W is the vocabulary size. Through Gibbs sampling, we iteratively update the topic assignments for each word and ultimately obtain the topic distribution θ_d for each document and the word distribution ϕ_k for each topic. Once topic assignments are inferred through Gibbs sampling, the topic distribution θ_d for document d can be estimated as:

$$\theta_d = \frac{n_{d,k} + \alpha}{n_d + K\alpha}$$

where $n_{d,k}$ is the frequency of topic k in document d_t, n_d is the total word count in document d_r and K is the number of topics. The word distribution ϕ_k for topic k can be estimated as:

$$\phi_k = \frac{n_{k,w} + \beta}{n_k + W\beta}$$

where $n_{k,w}$ is the frequency of word w in topic k_r, n_k is the total frequency of words in topic k_v and W is the vocabulary size.

Through these inference steps, the *LDA* model can extract latent topics from a corpus of documents and help us uncover the core cultural themes within the text. Combining *TF-IDF* and *LDA* allows us to conduct a comprehensive analysis of cultural narratives, understanding both the emotional and thematic evolution of the text. *TF-IDF* helps us identify the most emotionally and culturally significant keywords, while *LDA* uncovers the latent topics and cultural symbols behind these keywords. This combination provides strong support for the design of cultural narratives in virtual reality scenes and helps us gain deeper insight into the emotions and cultural significance embedded in different historical periods and cultural contexts.

VR scene modelling

Based on data analysis, this study uses the Unity engine to construct an immersive *VR* scene, integrating visual data and cultural narrative content into the virtual environment to provide users with a multi-dimensional experience. The goal of the *VR* scene construction is to achieve a high degree of reproduction of the visual landscape and a deep integration of the cultural narrative. *VR* modelling was selected due to its capacity to simulate immersive, multisensory interactions with historical and ecological landscapes. Unlike traditional 2D representations, *VR* allows users to experience spatial environments dynamically, thereby reinforcing spatial memory through embodied cognition and enhancing emotional engagement with landscape elements. This approach aligns with theories in environmental psychology and memory studies, which highlight immersion as a key driver of retention, affective response, and conservation motivation.

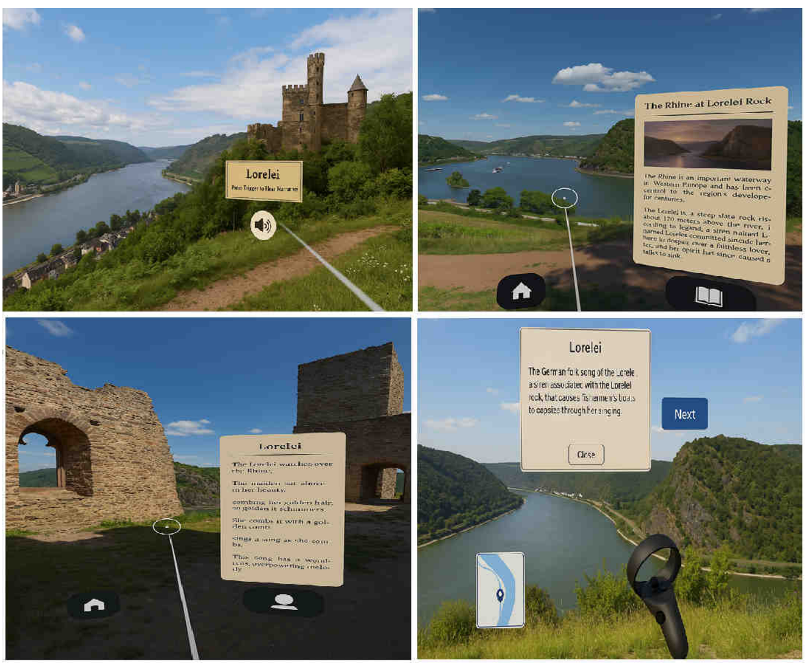


Fig. 3. Screenshots of Lorelei Rock embedded with cultural narrative data (source: created by author)

Firstly, virtual scenes of the Rhine Valley were reconstructed in Unity based on processed visual landscape data (e.g. 3D models and textures). These scenes include ancient castles, vineyard terraces and meandering rivers in the middle valley, realistically reproducing the landmarks of the region. Secondly, cultural narrative data is embedded into virtual scenes in various forms, such as audio narration, pop-up infoboxes and dynamic event triggering to present the narrative content of the Lorelei legend and the history of the old castle. Figure 3 shows an example of the screenshot for Lorelei Rock.

In terms of interaction function design, the study adds various interaction functions to the *VR* scene to enhance the user experience. For example, a virtual tour function was set up to allow users to freely explore key areas in the scene, and a historical event experience module was designed to allow users to 'experience' the narrative of the Lorelei legend or simulate the historical battles of the old castle. Through these interactive functions, users can not only visually perceive the landscape, but also deeply participate in the cultural narrative, strengthening memory and emotional resonance. Figure 4 shows an example of virtual experience of the old castle.

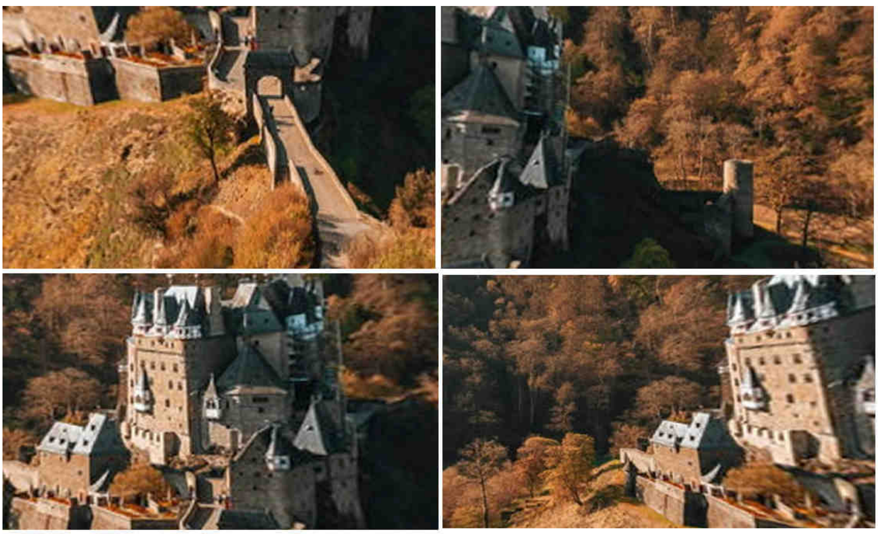


Fig. 4. *VR* experience of the old castle (source: created by author)

Survey experiment

The survey experiment design is a key part of this study, which verifies the effects of different landscape and narrative presentations on users' spatial memory and attitudes towards ecological conservation through group comparisons and assessment of test indicators.

Firstly, the experiment divided the participants into three groups: traditional picture presentation group, static *VR* group and narrative *VR* group. The traditional picture display group presented the Rhine landscape and cultural content through static pictures only; the static *VR* group provided an immersive visual experience without the cultural narrative; and the narrative *VR* group integrated the visual landscape with the cultural narrative, presenting a complete immersive experience through interactive scenes. This grouping design enables comparison of the differences in user experience between different combinations of technology and content.

Second, a variety of test metrics were designed to evaluate the experimental effects. The Memory Test Score is used to measure the depth of users' memory of the landscape and cultural content under different experiential modalities, and the test includes the recall of visual symbols, narrative details and spatial structure. The Ecological Conservation Intentions Questionnaire assessed users' attitude changes after the experience through a series of questions (e.g., "To what extent do you support the ecological conservation of the Rhine River?"), with a focus on analysing whether narrative *VR* scenarios can enhance users' awareness of and sense of responsibility for the conservation of the Rhine River.

Sustainability contribution modelling

In this study, we mainly adopt two models for sustainability contribution modelling: The Carbon Sink Capacity Analysis Model and Water Resource Regulation Model.

The Carbon Sink Capacity Analysis Model is used to assess the capacity of ecosystems to absorb and fix carbon dioxide through vegetation [54, 55]. The model integrates factors such as the area covered by vegetation, the absorption capacity per unit area and the type of vegetation. The model can be represented as an equation:

$$C_{seq} = A_1 \cdot D \cdot EF \tag{1}$$

where C_{seq} is the total carbon sink [t CO_2/year] (t = tonne = 10^3 kg = 10^6 g = Mg), A_1 is the area covered by vegetation [ha] (hectare = 10,000 m^2 = 10^4 m^2), D is the carbon sink density per unit area [t CO_2/ ha·year], EF is the carbon sink efficiency factor (efficiency coefficient of CO_2 absorption by different types of vegetation).

The Water Resource Regulation Model is used to assess the function of ecosystems in regulating the water cycle and mitigating floods and droughts [56]. The model simulates the ability of different landforms and vegetation types to regulate water resources by calculating elements such as precipitation, evaporation, infiltration and runoff. The model can be represented as equation:

$$W_{reg} = A_2 \cdot R \cdot C \tag{2}$$

where W_{reg} is the volume of water regulation [1000 m^3/year], A_2 is the area of the region [ha], R is the average annual precipitation [m/year], C is the regulation coefficient (water regulation capacity of different landscape types, e.g. wetlands, forests, etc.).

Results and discussion

The dual role of ecological and cultural landscapes

The local landscapes of the Rhine basin show a significant dual role in the ecological and cultural dimensions, especially in the shaping of spatial memory through the interaction of landscape symbols and cultural narratives. The results show that these landscape symbols (e.g. castles, river valleys) are not only highly attractive in the visual dimension, but are also endowed with deep emotional and cultural values through cultural narratives, which significantly enhance users' memories and identifications of the local landscapes.

In Figure 5, it illustrates the emotional and thematic keywords and their importance in the historical narrative of the Rhine Valley. Keywords such as 'Romanticism' and 'Nostalgia' highlight the influence of the Romantic movement on the poetic portrayal of the Rhine, as well as the nostalgia for a peaceful and traditional past in the context of modernisation and war. Nostalgia for the peaceful and traditional life of the past in the context of modernisation and war. In addition, 'Pride' and 'Awe' reflect national pride and admiration for the natural and historical heritage of Germany during the period of unification and cultural renaissance. Themes such as ‘War’, ‘Peace’ and ‘Unification’ emphasise the role of the Rhine as a witness to historical events. Themes such as ‘War’, ‘Peace’ and ‘Unification’ emphasise the role of the Rhine as a witness to historical events and demonstrate its symbolic significance in war, unification and cultural revival.

Fig. 5. Cloud of emotional and thematic keywords in historical narrative of the Rhine Valley

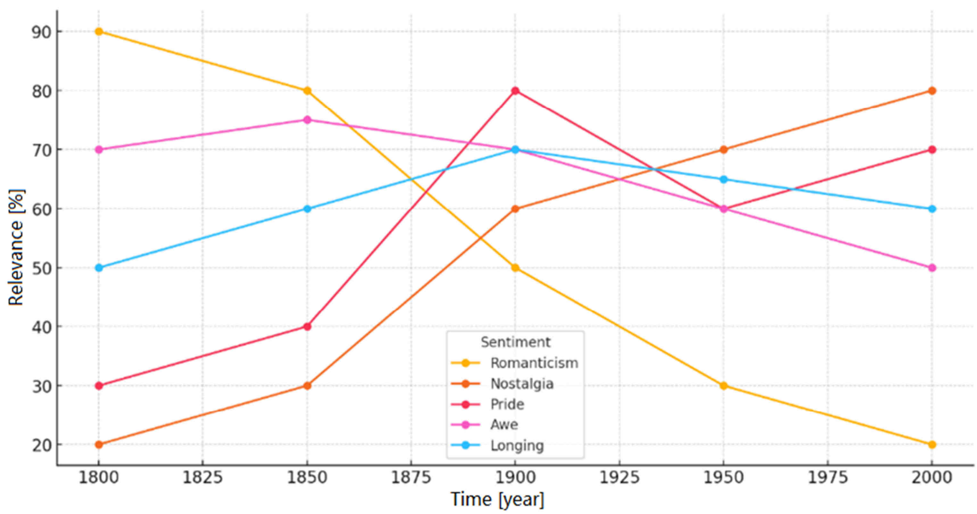


Fig. 6. Historical sentiment intensity trends

In this study, we also analyse the historical sentiment intensity from the narrative data as shown in Figure 6. We can see that Romanticism reached its peak between 1800 and 1850, reflecting the Romantic movement’s high regard for the natural beauty and cultural symbols of the Rhine. As industrialisation and modernisation progressed, this sentiment waned, falling to a lower level by the year 2000. Nostalgia has grown with historical events, especially after the two world wars and social reconstruction of the 20th Century and peaked in the 2000s with a stronger sense of nostalgia for the peaceful and traditional life of the past. Pride rose rapidly after the reunification of Germany in 1871, reflecting increased national unity and cultural identity. Despite fluctuations after World War II, Pride gradually recovered and remained high with European integration and cultural revival. Awe for the natural and cultural heritage of the Rhine has remained high throughout the period, especially during the Romantic period of the 19th century, and continues to have a significant impact in modern times. Longing, which expresses a longing for an idealised life and a simpler time in the past, has remained relatively constant in intensity throughout the 20th century because of modernisation and social change.

Figure 7, it illustrates the key words at the heart of the Rhine Valley's cultural narrative, reflecting its rich cultural identity and deep historical significance. 'Castle' and 'Lorelei' highlight the region's iconic architecture and myths and legends, symbolising romanticism and mystical culture; 'Vineyard' and 'Wine' emphasise the importance of agricultural traditions and food culture. 'Heritage' and 'Tradition' express the importance of cultural preservation and local identity, while 'Legends' and 'Mythology' show the richness of folk tales and historical narratives. In addition, 'Art', 'Music' and 'Poetry' further emphasise the Rhine as a source of inspiration for cultural creativity.

Fig. 7. Cloud of the key words at the heart of the Rhine Valley's cultural narrative

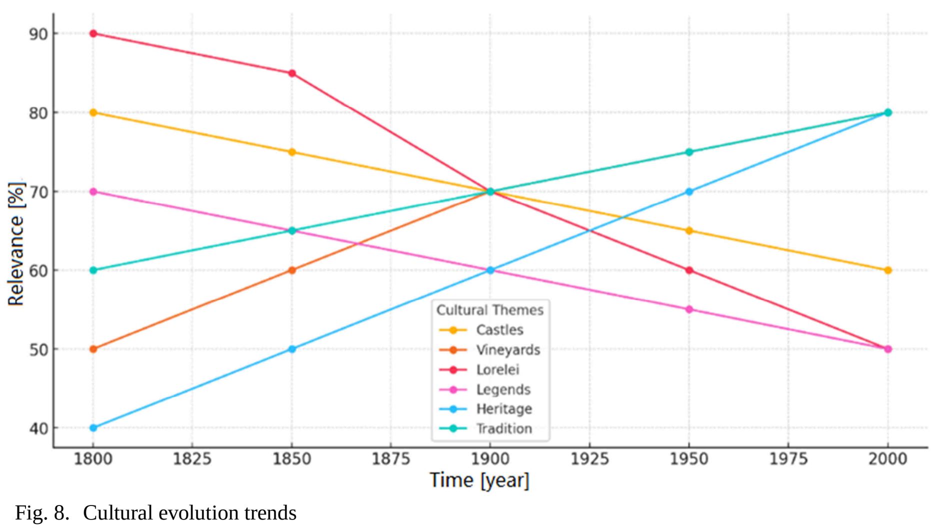


Fig. 8. Cultural evolution trends

Similarly, we analysed the historical evolution of culture. Figure 8 shows how the different cultural themes of the Rhine Valley have evolved over time: Castles have always maintained a high level of importance as cultural symbols, but their symbolic significance has declined slightly with modernisation; Vineyards have gradually increased in relevance, reflecting the growing importance of agriculture and tourism for the local economy and culture. Lorelei reached its peak in the 19th century during the period of Romanticism, but its modern influence has gradually weakened; Legends have also gradually faded with the rise of modern narratives. Heritage and Tradition, on the other hand, have shown a continuous growth, indicating the increasing importance that modern society attaches to cultural preservation and local identity.

Survey results

The experimental data showed that participants in the narrative *VR* group performed significantly better on the memory test than the static *VR* group and the traditional picture display group. The statistical results of the memory test scores are in Table 4.

Table 4

Memory test scores

Group	**Mean score (out of 100)**	**Standard deviation**
Narrative *VR* group	87	5.6
Static *VR* group	72	7.8
Traditional picture display group	65	8.3

Analysis of variance (ANOVA) results showed that the difference in memory test scores between these three groups was significant ($p < 0.01$). Further post hoc tests showed that the scores of the narrative *VR* group were significantly higher than the other two groups. This suggests that the cultural narrative and visual elements integrated in the narrative *VR* scenes were effective in facilitating participants' memory formation for the landscape.

In terms of recalling the depth and details of the content, participants in the Narrative *VR* group showed greater ability. For example, more than 80 % of the participants were able to accurately describe historical events or cultural details in the virtual scene, such as the plot of the Lorelei legend and the architectural features of the old castle. In contrast, participants in the static *VR* group and the traditional picture display group were more limited to describing the surface features of the landscape (e.g., "the river is beautiful" and "the old castle is tall"), and lacked the in-depth memorisation characteristics of the narrative *VR* group.

The immersion of *VR* technology not only enhances the ability to memorise, but also significantly increases the public's interest and willingness to participate in landscape conservation. In the ecological protection willingness questionnaire, participants in the narrative *VR* group showed a stronger sense of motivation and responsibility, as shown in Figure 9.

These data suggest that narrative *VR* scenes can more effectively stimulate public awareness of ecological protection and participation behaviour through immersive experiences and emotional triggers. Further analysis found that immersion is a key factor in enhancing participation. In the user satisfaction survey, the immersion rating of the narrative *VR* group averaged 4.8 (out of 5), higher than the 4.2 of the static *VR* group and the 3.5 of the traditional picture display group. Participants gained a stronger sense of scene immersion in the narrative *VR* scene by interacting with the virtual environment (e.g., guided tour of historical events, triggering of dynamic information), which enhanced their sense of identification with and willingness to take action on landscape conservation.

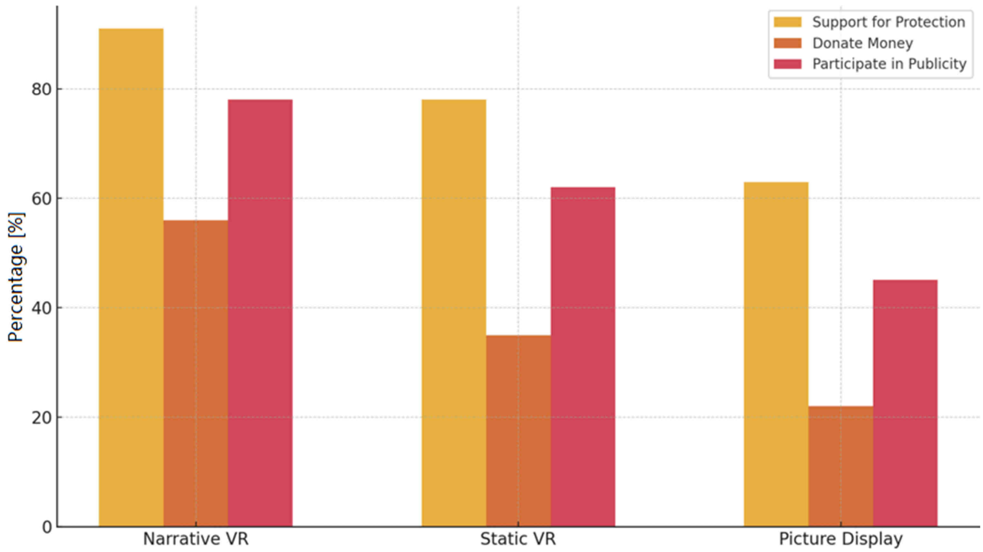


Fig. 9. Results of ecological protection willingness questionnaire

Through the experiments, we found that the enhancement effect of *VR* technology is not only reflected in the ability to memorise and the willingness to participate, but also in the emotional resonance and the depth of the user's visual experience. Participants' stronger recall and emotional engagement with culturally symbolic sites such as the Lorelei Rock reinforce the theoretical notion that cultural narratives amplify the meaning-making potential of ecological landscapes. These results support the idea that *VR* does not merely deliver environmental knowledge but serves as a conduit for memory-based attachment and heritage appreciation, aligning with landscape ecology's emphasis on cultural services. In narrative *VR* scenes, participants showed higher emotional identification through dynamic cultural narratives and ecological feature perception. For example, users rated the historical event experience module (e.g., the Lorelei Legend dynamic scene) at 4.7 (out of 5), whereas they rated the cultural content of the traditional picture display group at only 3.9. In addition, the reproduction of visual details and dynamic environments by *VR* technology enhanced the overall user experience. For example, in the narrative *VR* group, the dynamic effects of vegetation, the natural simulation of river currents, and the 3D detail reproduction of ancient castles resulted in a 4.9 (out of 5) rating for participants' visual experience of the landscape. This high-quality visual effect further strengthened users' immersion and depth of memory of the landscape.

Analysis of sustainability contribution

Based on the ecological data we collected, this study found that the area around the cultural landmarks is particularly strong in terms of carbon sinks, water regulation and other ecological functions.

To calculate the carbon sink level, we set a sample calculating region (A_1) as 100 ha and calculate carbon sinks in two types of areas: landmark and non-landmark. In this study:

- A_1 is the area covered by vegetation [ha],
- D is the carbon sink density per unit area [t CO_2/ ha · year]
- EF is the carbon sink efficiency coefficient (efficiency coefficient of CO_2 absorption by different types of vegetation). In landmark area, its annual CO_2 absorption capacity is 4.5 t CO_2/ha · year (EF_{lmk} = 4.5).

(1) Calculation of carbon sink capacity in cultural landmark areas is:

$$C_{lmk} = A_{lmk} \cdot 4.5 \text{ [t } CO_2\text{/ha} \cdot \text{year]}$$

We set the cultural landmark areas as 30 ha (30 % of the total areas), its carbon sink capacity is $C_{lmk} = 30 \cdot 4.5 = 135$ t CO_2/ha · year.

(2) Calculation of carbon sink capacity in non-cultural landmark areas

The non-landmarked area has a low vegetation cover of 58 % and is assumed to have an absorptive capacity of 80 % of the landmark area in our study.

$$EF_{non\text{-}lmk} = EF_{lmrk} \cdot 0.8 = 4.5 \cdot 0.8 = 3.6 \text{ t } CO_2\text{/ha} \cdot \text{year}$$

Thus, its carbon sink capacity is $C_{\text{non-}lmk} = 70 \cdot 3.6 = 252$ t CO_2/ha · year

The total carbon sink capacity in the sample (100 ha) is

$$C_{total} = C_{lmk} + C_{non\text{-}lmk} = 135 + 252 = 387 \text{ t } CO_2\text{/ha} \cdot \text{year}$$

According to the modelling, cultural landmark areas have significantly higher carbon sink capacity per hectare than non-landmark areas by about 20 % due to their high vegetation cover (72 %). In the analysis of the total area of 100 ha, the contribution of cultural landmarks reaches 35 % of the total carbon sinks, despite the relatively small share of cultural landmarks. This suggests that improving vegetation management and carbon sink capacity in cultural landmark areas has an important role to play in the overall level of regional carbon sinks.

The high regulation coefficients of the wetland and forest areas are crucial for the water regulation capacity. The total average annual runoff of the Rhine basin is about 83.25 billion cubic meters, of which the wetland and forested areas contribute about 46.7 % of the water regulation capacity. To calculate the overall water resource regulation capacity, we take a sample calculating watershed area (A_2) as 500 ha (the total basin area of Rhine River is 18,500,000 ha). We assume that wetlands, forests and other areas account for 30 %, 40 % and 30 % of the total area, respectively. While the regulation coefficients of different areas are: $C_{wetland} = 0.8$, $C_{forest} = 0.6$ and $C_{others} = 0.3$ (i.e. grassland, farm land), the average regulation coefficient is:

$$C_{avg} = 0.3 \cdot 0.8 + 0.4 \cdot 0.6 + 0.3 \cdot 0.3 = 0.6$$

According to the ICPR, the average annual precipitation (P) of Rhine River is about 800 mm - 1200 mm, in this study, we take the median value of 1000 mm (R = 1).

Thus the total water regulation is:

$$W_{reg} = A_2 \cdot R \cdot C = 500 \cdot 1 \cdot 0.6 = 300 \cdot 1000 \text{ m}^3\text{/year}$$

The area surrounding the cultural landmark (assumed to be 150 hectares, or 30 % of the total area) consists primarily of wetlands and forests. Assuming 50 % wetlands and 50 % forests, the regulation coefficient is:

$$C_{lmk} = 0.5 \cdot 0.8 + 0.5 \cdot 0.6 = 0.7$$

Thus, the water regulation in cultural landmark areas is:

$$W_{lmk} = 150 \cdot 1 \cdot 0.7 = 105 \cdot 1000\ m^3/year$$

The remaining area is 350 ha, with a regulation coefficient as 0.6. therefore, the water regulation in the remaining areas is:

$$W_{non\text{-}lmk} = 350 \cdot 1 \cdot 0.6 = 210 \cdot 10^3\ m^3/year$$

So the total water regulation is:

$$W_{total} = W_{lmk} + W_{non\text{-}lmk} = 105 + 210 = 315 \cdot 10^3\ m^3/year.$$

The contribution of landmark area is $W_{lmk} / W_{total} = 105/315 \cdot 100\ \% = 33.3\ \%$.

The high proportion of wetland and forest in the cultural landmark area makes its contribution to the overall water resource regulation capacity of the watershed reach about 33.3 %. This proves that reasonable protection of wetland and forest ecosystems can help to enhance the water regulation capacity and ensure the ecological safety and sustainable development of the watershed.

Conclusion

This study emphasises the crucial role of Rhine landscapes in shaping spatial memory and supporting ecological conservation. The integration of visual symbols (e.g., castles, valleys, terraces) and cultural narratives significantly enhances public engagement. Experimental results show narrative-based *VR* notably improved spatial memory, with 85 % accurate recall of historical and ecological details, compared to 72 % in static *VR* and 65 % in traditional groups. Furthermore, 91 % of participants supported conservation initiatives that integrated cultural and ecological values, confirming the effectiveness of combined strategies.

The research also confirms *VR*'s efficacy in enhancing emotional connection and information retention, with 78 % of participants reporting greater effectiveness compared to traditional learning methods. These findings suggest that immersive *VR* technology can serve as a powerful educational tool, strengthening public engagement in landscape conservation.

Based on these insights, several practical recommendations are proposed:

(1) Integrate Immersive *VR* in Public Education: Incorporate *VR* experiences highlighting ecological and cultural landmarks into educational programmes and museums to enhance conservation awareness.

(2) Promote *VR* in Sustainable Tourism Development: Adopt *VR* storytelling for eco-tourism initiatives, engaging broader audiences while reducing environmental impacts on sensitive landscapes.

(3) Implement Policy Incentives for Digital Heritage Projects: Encourage governments and cultural organisations to support digitisation of ecological landscapes, preserving heritage and promoting wider access.

(4) Foster Stakeholder Collaboration in *VR* Content Creation: Promote partnerships among ecologists, historians, *VR* developers, and local communities to produce authentic, engaging *VR* content.

(5) Incorporate *VR* Landscape Modules in School Curricula: Integrate *VR* modules into formal education, fostering early spatial learning and sustainability awareness among younger generations.

Despite these contributions, limitations include the study's geographic specificity (Rhine Basin), limited participant diversity and sample size, technical constraints in ecological detail representation, high *VR* development costs, and reliance on simple analytical methods. Future research should expand to diverse cultural landscapes, involve broader demographic samples, utilise advanced analytical methods (e.g., machine learning), and explore the long-term behavioural impacts and scalability of *VR* technologies.

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