The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLVIII-M-9-2025
30th CIPA Symposium "Heritage Conservation from Bits:
From Digital Documentation to Data-driven Heritage Conservation", 25–29 August 2025, Seoul, Republic of Korea

Innovative Digital Technology in Education about Paleolithic Sites: A Case Study of the Peking Man Site at Zhoukoudian

Jianhua Wei [1], Wei Li [2], Shize Zhou [2], Yan Zhang [2], Tong Yu[2], Dezhi Peng [2], YingHua Ma [2]

[1] Zhoukoudian Peking Man Site Management Office, Beijing, China - 1358657521@qq.com
[2] Tsinghua Heritage Institute for Digitalization Co., Ltd (THID), Beijing, China
(liwei, zhoushize, zhangyan, yutong, pengdezhi, mayinghua)@thid.cn

Keywords: Virtual Reality, LBE VR, Heritage Education, Paleolithic sites, Peking Man, Zhoukoudian.

Abstract

With the rapid advancement of innovative digital technologies, such as location-based entertainment virtual reality (LBE VR), users can now fully immerse themselves in interactive and navigable virtual environments. While virtual reality (VR) has increasingly been applied in cultural heritage education, research specifically focusing on the use of LBE VR for education about paleolithic sites remains limited. This study explores the potential of LBE VR technology to enhance participatory learning of adolescents at paleolithic heritage sites. Using a multiple-case qualitative design, we gathered semi-structured interviews from 57 secondary-school students (aged 15-17) who participated in an LBE VR programme. Focusing on the Peking Man Site at Zhoukoudian, and using the LBE VR immersive experience "I Am Ape-man: A Day into the Life of Peking Man." as a case study, the article assesses the impact of this technology on education about paleolithic history. The findings demonstrate that LBE VR effectively facilitates deeper engagement with the history and culture of early humans. This study provides empirical evidence supporting the integration of LBE VR into paleolithic site education and offers insights into the design of innovative educational applications and pedagogical strategies.

1. Introduction

Virtual Reality (VR) has emerged as a critical tool in the field of cultural heritage presentation, offering immersive experiences that not only heighten public awareness and appreciation of cultural heritage, but also provide innovative approaches to heritage education. Enhancing cultural heritage education through VR has become a key focus in the interdisciplinary research at the intersection of VR technology and heritage presentation. Numerous studies have highlighted the potential of VR in advancing cultural heritage education. According to VR, grounded in three core principles—Immersion, Interaction, and user engagement with both the environment and narrative—holds significant potential in education by making the learning process more motivating and immersive (Freina and Ott, 2015). Among the emerging trends, location-based entertainment virtual reality (LBE VR) technology stands out as a new form of offline interactive experience. Unlike traditional VR, LBE VR allows users to explore large physical spaces (typically over 100 square meters) while wearing head-mounted displays (HMDs), providing an immersive, narrative-driven experience based on the plot's progression. This new VR mode offers an innovative approach to engaging visitors with historical and cultural stories.

Although the broader use of VR in cultural heritage education has gained momentum, the specific application of LBE VR technology in heritage education, particularly at paleolithic sites, remains a relatively new and under-explored area. This paper aims to fill this gap by investigating the integration of LBE VR at the Peking Man Site at Zhoukoudian, a UNESCO World Heritage site. Paleolithic archaeological sites are generally characterized by highly specialized knowledge, limited visibility at the excavation site, and value interpretations that are often abstract and difficult to understand, making them seem remote and unfamiliar to modern audiences. The display and education of ancient human sites have traditionally focused on fossil exhibits, while information related to paleogeology, paleontology, and prehistoric ecological environments tends to be presented in a fragmented manner, lacking systematic, holistic narratives and intuitive displays.The study offers empirical into the effectiveness, challenges, and educational value of incorporating LBE VR into education of adolescents about paleolithic sites, with implications for pedagogical design and the future application of VR in paleolithic contexts.

LBE VR technology transports adolescents to places often deemed inaccessible, with a prominent example being the immersive experience "I Am Ape-man: A Day into the Life of Peking Man." at the Peking Man Site at Zhoukoudian. The programme was completed and launched in March 2025. This programme allows users to explore the prehistoric environment of the cave where Peking Man once lived, showcasing the potential of LBE VR to create engaging and educational activities centered on paleolithic sites. This paper will examine how LBE VR is transforming cultural storytelling at the Peking Man Site, highlighting the technology's significant role in enhancing paleolithic sites education of adolescents.

1.1 Location-Based Entertainment Virtual Reality (LBE VR)

VR is defined as a complex technology which exploits existing technologies (e.g., 3D graphics, robotics, etc.) to create an immersive and interactive digital environment (Carrozzino and Bergamasco, 2010). It has been adopted as one of the various digital technologies for documenting and preserving.A virtual world is a computer-simulated environment, and virtual reality (VR) can be defined as a simulated experience (Cecotti, H.,2022). LBE VR is an innovative VR application for education and cultural experiences, featuring a large-scale, multi-user virtual environment. This technology is designed to accommodate multiple users, allowing them to walk freely within an expansive tracking area and share a larger virtual space.

1.2 Peking Man Site at Zhoukoudian

The Peking Man Site at Zhoukoudian has been inscribed in UNESCO World Heritage Site list since 1987, representing the human communities of the Asian continent from the Middle Pleistocene to the Palaeolithic Period, illustrating the process of human evolution. Located in the North China Plain,this site lies about 42 km south-west of Beijing. Natural limestone caves in this area provided an optimal survival environment for early humans. So far, ancient human fossils, cultural artifacts and animal remains from 23 localities within the site dating from 5 million years ago to 10,000 years ago have been discovered by scientists. These include the remains of Homo erectus pekinensis (Peking Man), who lived in the Middle Pleistocene (700,000 to 200,000 years ago). At the same time, fossils of hundreds of animal species, over 100,000 pieces of stone tools and evidence of Peking Man using fire have been discovered. There is a natural cave about 140 meters long from east to west on the mountain, commonly known as the “Ape Man Cave”. After the first discovery of ancient human remains in this cave in 1929, it was called “The locality 1 archaeological site at the Zhoukoudian Peking Man cave” (e.g., Figure 1). The discovery of fire remains at the site has pushed back the history of human use of fire by hundreds of thousands of years. Five layers of ash deposits, three ash piles and a large number of burnt bones were discovered at the site. The thickest layer of ash could reach up to six meters. These relics indicate that Peking Man not only knew how to use fire but also could preserve fire sources. In brief, as the site of significant hominid remains discovered in the Asian continent demonstrating an evolutionary cultural sequence, Zhoukoudian is of major importance within the worldwide context.

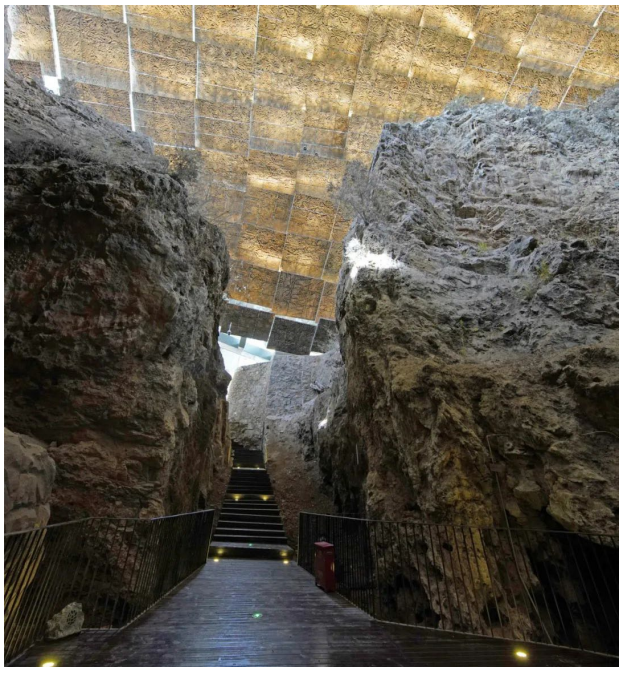

Figure 1. The current situation of locality 1 archaeological site at the Zhoukoudian Peking Man cave.

Understanding the origins of humanity and the evolutionary path of human society is essential for recognizing the diversity and commonality of human life, behavior, and experience across the globe. However, due to the challenges the public faces in accessing information about key human origin sites, these locations often fail to receive the attention they deserve. “I am Ape-man: A Day into the Life of Peking Man” offers an innovative LBE VR experience focused on human origin sites in World Heritage. Based on the locality 1 archaeological site at the Zhoukoudian Peking Man cave, this project utilizes LBE VR technology to create an immersive and interactive experience (e.g., Figure 2). The technology enables precise positioning and navigation, facilitates real-time interaction among multiple users, and breaks through traditional spatial and temporal limitations. By donning head-mounted displays (HMDs), users can engage with the life of Peking Man from a first-person perspective, allowing them to collaboratively explore the mysteries of human origins in the Peking Man cave as it existed hundreds of thousands of years ago.

Figure 2. Location-Based Entertainment Virtual Reality (LBE VR) experience.

2. Application characteristics of LBE VR technology

2.1 Large Space

Large space offers substantial advantages in enhancing user experience by accommodating more users, supporting complex interactions, and enabling freer movements. Traditional VR experiences are often confined to fixed perspectives, where users passively acquire information. In contrast, LBE VR overcomes these limitations by allowing users to move freely within expansive virtual environments, exploring the scene’s every detail . This freedom of movement fosters a deeper sense of immersion and engagement, transforming users from passive spectators into active participants, and even integrating them into the story narrative. As a result, users experience more dynamic scenes and interactive activities, making the virtual experience not only more realistic but also more enjoyable. While LBE VR requires high-end hardware, such as multiple motion tracking systems and powerful computing resources, the large space feature has obvious advantages in enhancing immersive experiences. In conclusion, LBE VR opens new possibilities for the development and application of virtual reality, driving further advancements in immersive technologies.

2.2 Free Roaming

In LBE VR, Free Roaming is essential for creating immersive experiences. Advanced positioning and tracking technologies enable users to move and explore freely within virtual environments, significantly enhancing their sense of presence. Motion capture systems facilitate actions such as walking, running, jumping, and interacting with virtual objects, which are accurately reflected in the virtual world, thereby intensifying

immersion and presence. The precision of tracking technology is fundamental to Free Roaming, ensuring that user movements and interactions in the virtual space are fluid and natural. By accurately tracking basic human movements, such as gestures, facial expressions, and body postures, motion capture technology supports intuitive and engaging interactions.

The key advantages of motion tracking in LBE VR are high precision and low latency, both of which are crucial for seamless real-time interactions. In larger physical spaces, Free Roaming offers a more intuitive and flexible mode of interaction, enabling users to explore the virtual environment in a more natural way. This enhances users' understanding of the virtual world, unlocking its potential in fields such as education and entertainment, and providing richer, more authentic experiences (Slater and Wilbur, 1997).

2.3 Audio-Visual Perception

The immersive experience in LBE VR is primarily shaped by audiovisual perception, which plays a crucial role in user immersion. For learners who prefer visual, auditory, or kinesthetic modalities, VR serves as an effective tool for exploring, understanding, and retaining new knowledge (Leite, et al., 2010). Sight and hearing are two senses that play a vital role in scene understanding. High-resolution visuals and precise perspective rendering allow users to explore expansive virtual environments. For instance, head-mounted displays (HMDs) with high resolution deliver detailed virtual scenes, while real-time rendering technologies like Unreal Engine and Unity ensure seamless, dynamic image generation based on user movement, enhancing visual realism. In parallel, spatial audio further enriches the experience by simulating directional sound and distance, improving spatial awareness and the overall sense of presence. The incorporation of ambient sounds, such as wind or animal noises, further amplifies immersion by reinforcing the auditory realism of the virtual environment.

However, these technologies have limitations. Visually, even with high-resolution displays, complex scenes may introduce delays, resulting in unnatural transitions and disrupting immersion. Auditory challenges, such as sound muddling or inaccurate spatial directionality, may also emerge in densely layered soundscapes. Ideally, complete immersion in a virtual environment would engage all five senses, but most current VR experiences stimulate only a limited number of them (Freina and Ott, 2015). Despite these constraints, audiovisual perception remains essential for simulating real-world sensory experiences, particularly through vision and hearing, which together create a convincingly immersive virtual environment (Slater & Wilbur, 1997). In conclusion, audiovisual perception is a critical element in LBE VR, as it constructs a virtual world that closely mimics reality in both visual and auditory dimensions.

2.4 Social Interaction

Social interaction constitutes a fundamental application area in LBE VR environments. Central to this is multi-user experience technology, which enables users to both visualize and interact with each other within shared virtual spaces. This interaction significantly enhances the social and immersive qualities of the virtual experience. Users’ perception and interaction with avatars representing others in real time cultivate a sense of presence and social connection, differentiating it from traditional virtual reality environments. LBE VR systems are designed to support the simultaneous presence of multiple users within a common virtual setting, generating dynamic avatars (e.g., Figure 3) that correspond to real-world movements in real time . During these immersive interactions, individuals frequently focus on the avatars of others, enabling real-time communication and collaborative exploration. One example of such interaction might involve users responding to each other’s actions, such as laughing at a humorous gesture or reacting to unexpected behavior in the virtual space. This social engagement not only enhances the interactivity of the experience but also adds an element of entertainment, which increases its appeal.

However, the fidelity of avatar representations often falls short of perfectly mirroring human expressions and movements, potentially undermining the authenticity of social exchanges. Despite these limitations, the benefits of multi-user VR environments are considerable. The shared experience facilitated by such spaces aligns well with the entertainment needs of diverse groups, including families, couples, and friends. In conclusion, the potential of LBE VR to transform social interactions by fostering deeply interconnected environments is indisputable.

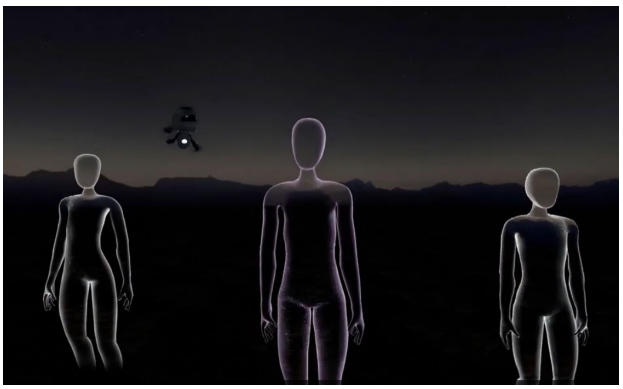

Figure 3. Avatars representing others.

3. Narrative-Driven

Immersive experience creators are increasingly using LBE VR to elevate storytelling. The work “I am Ape-man: A Day into the Life of Peking Man” employs LBE VR technology to offer a novel narrative approach for interpreting the Peking Man Site at Zhoukoudian. This immersive experience not only enriches the heritage narrative but also enhances site engagement and facilitates situational learning.

3.1 Script Characteristics

An in-depth study should be conducted on the natural environment, landforms, original appearance of the Peking Man Cave, as well as the flora and fauna, physical characteristics of Peking Man, and their survival environment and behaviors during the period when Peking Man inhabited the Zhoukoudian area. This includes evidence of fire use, stone tool production and utilization, hunting and gathering, and communal living. Close collaboration with experts is essential, with all details and descriptions in the script undergoing rigorous review and verification based on scientific validation by paleoanthropologists to ensure accuracy and authenticity. Additionally, the interior and surrounding environment of the Peking Man Cave were accurately reconstructed at a 1:1 scale using virtual modeling , with the limestone texture authentically represented (e.g., Figure 4).

Figure 4. The virtual reconstruction of the Peking Man Cave interior.

The work “I am Ape-man: A Day into the Life of Peking Man” employs an engaging linear narrative technique. In this story, the non-player character (NPC), “Yuan Yuan”, a Peking Man, is introduced (e.g., Figure 5). The virtual character “Yuan Yuan”, serves as a cultural communication IP for the Peking Man Site at Zhoukoudian. By presenting a more vivid and engaging representation, it bridges the gap between the public and ancient human culture, making it more accessible, particularly to younger audiences. This aligns with the paleolithic site's educational and popular science objectives, fostering greater engagement with the history of early humans. The users follows “Yuan Yuan” through various life scenes of the “Peking man”, with the entire immersive expedition structured around a timeline. This linear narrative approach guides users through the story in a predetermined sequence, allowing them to absorb information in an organized manner within the virtual space. As a result, it facilitates a deeper understanding of the living environment and conditions of Peking Man. Moreover, storytelling has played a significant role in attracting visitors’ attention to the popular science of human origins and evolution. However, the linear structure, while effective, limits users' ability to explore the content from diverse perspectives. Nonetheless, the clarity and conciseness with which the linear narrative conveys scientific knowledge related to ancient humans cannot be denied. This immersive expedition, grounded in a linear narrative, offers valuable insights for popular science education.

Figure 5. Cultural Communication IP, “Yuan Yuan”.

The entertainment value of a script can provide participants with a profound experience that blends both psychological and physical engagement. The enjoyment primarily stems from the "realistic" experience generated by the seamless integration of intricately designed plots and immersive visual effects. For instance, visitors embark on an exhilarating bird’ s-eye tour of Longgushan, offering them a unique opportunity to explore the survival environment of Peking Man as never before. This LBE VR journey allows participants to soar over lush landscapes and view the Peking Man cave from above. As participants stand on ascending leaves, they experience the instability of their center of gravity, evoking a psychological fear of heights. Additionally, the script’s engaging plot elements further amplify its entertainment value. For example, during the leaf flight effect, participants experience the sensation of intentionally stepping into mid-air, generating a novel excitement within the virtual world. At the entrance of the ape-man cave, where participants must bend over to pass, they deliberately walk upright, creating a deeper sense of immersion. Similarly, when observing the making of Peking Man stone tools, the audience is prompted to reach out to interact with the tools, fostering a closer understanding of Peking Man's daily life. In another instance, participants transform into a giant and look down upon the Zhoukoudian site, gaining a macroscopic perspective on the location where the fossils were unearthed. This shift in perspective enhances the sense of engagement and curiosity. However, it is important to note that individual differences may affect some participants’ ability to fully immerse themselves in the experience crafted by the script.

3.2 Scenarios Design

The virtual expedition spans approximately 12 minutes and is divided into four main segments. The prologue, titled “Initial Teaching”(e.g., Figure 6), introduces the non-player character (NPC) Peking Man “Yuan Yuan”, who guides visitors into the virtual space of the locality 1 archaeological site at the Zhoukoudian Peking Man cave, initiating the LBE VR expedition. In the second segment, “Return to Longgushan”, visitors are given an aerial view of the Zhoukoudian area as it appeared hundreds of thousands of years ago. The scene showcases the mixed coniferous and broad-leaved forests, the Zhoukoudian River, Longgushan, and other natural environments, offering an introduction to the living conditions of Peking Man. Visitors are then immersed in the primeval forest, where they can engage in hunting and gathering activities alongside Peking Man, e.g. Figure 7. The third segment, “Life in the Cave”, presents a detailed portrayal of Peking Man’s daily life within the cave, depicting various activities such as roasting meat over fire and crafting stone tools, e.g. Figure 8. The final segment, “Modern Zhoukoudian”, provides a surreal visual experience by allowing the visitors to adopt the perspective of a giant and explore present-day Zhoukoudian, e.g. Figure 9. As visitors moves through the site, representative ancient human and animal fossil locations are gradually illuminated, narrating the ongoing sequence of human evolution and highlighting the cultural significance of the Peking Man site at Zhoukoudian . Additionally, the virtual expedition offers an enriching interactive experience, allowing visitors to "touch" various stone tools and animal bones, as well as explore the details of the cultural relics in a 360° view.

Figure 6. “Initial Teaching” Segment.

Figure 7. “Return to Longgushan” Segment.

Figure 8. “Life in the Cave” Segment.

Figure 9. “Modern Zhoukoudian” Segment.

4. Design presentation

4.1 Character design

In the LBE VR environment, cartoon-style “Peking Man” characters design (e.g., Figure 10) can enhance adolescents’ sense of immersion and improve learning outcomes during educational activities. These character designs are rooted in archaeological evidence, including physical traits such as height (156 cm for adult males and 144 cm for females), skull bone thickness (twice that of modern humans), a low, flat forehead, and prominent brow ridges, providing a scientifically grounded framework. The proportions and color adjustments further enhance the characters' appeal, making them both engaging and accessible. For example, key features, such as the prominent brow ridges, are preserved while avoiding excessive realism. Additionally, the Peking Man’s clothing is designed using various animal furs, consistent with historical accuracy. This cartoon-style approach strikes a balance between historical authenticity and educational suitability within the virtual environment. By increasing accessibility for adolescents, the design transforms prehistoric humans from passive museum exhibits into interactive learning subjects. Drawing on scientific evidence, the cartoon-style characters not only enrich the educational experience but also foster emotional engagement within the virtual world. In LBE VR educational activities, this approach effectively facilitates the dissemination of knowledge about prehistoric humans while stimulating adolescents' interest in the subject.

Figure 10. Cartoon-style "Peking Man" characters design.

4.2 Venue Design

In designing large-space venues, integrating spatial positioning points with specific cultural elements is essential for enhancing educational activities. These positioning points enable precise location tracking and interaction within LBE VR environments, improving user experience when effectively implemented. When combined with cultural elements, they significantly increase the immersion and appeal of educational content, enabling adolescents to better understand the cultural and historical significance of an archaeological site in a virtual context. For instance, in the LBE VR immersive expedition “I am Ape-man: A Day into the Life of Peking Man”, spatial positioning points are paired with cultural elements such as “Yuan Yuan” (the Peking Man), mammoths, and other prehistoric species (e.g., Figure 11). These elements not only serve to positioning purposes but also reinforce the site’s image and engage adolescents with the concepts of ancient biology.

In the reception area, the use of decorations like ancient plants elements creates a prehistoric forest ambiance, further enhancing the immersive experience. The selection and arrangement of cultural elements in positioning points must be carefully designed to ensure both accuracy and educational value. In conclusion, integrating spatial positioning points with cultural elements in LBE VR venues offers an innovative

approach to teaching, e.g. Figure 12. This combination deepens adolescents’ understanding of archaeological sites, fostering a more engaging and immersive learning experience.

Figure 11. Specific Cultural Elements.

Figure 12. Integrating spatial positioning points with specific cultural elements.

5. Research method

This study employed a multiple-case qualitative design to explore adolescents’ experiences of creating and interacting with a narrative-driven LBE VR heritage project. 57 students aged 15-17 were selected as cases . All participants and their guardians provided informed consent prior to data collection. The multiple-case approach enabled us to examine how varying group dynamics, spatial navigation strategies, and levels of narrative engagement shaped learners’ perceptions of LBE VR.

Data were gathered through semi-structured interviews conducted. Each 30-minute session combined close-ended items—five-point Likert scales assessing usability satisfaction, narrative coherence, and collaborative engagement—with open-ended prompts designed to elicit rich reflections on cognitive and affective dimensions of the experience. Interview questions were framed by Experiential Learning theory (Kolb, 1984) and Narrative Transportation theory (Green & Brock, 2000), ensuring that both the practical mechanics of free-roaming navigation and the emotional impact of story immersion were thoroughly probed. All interviews were audio-recorded and subsequently transcribed verbatim.

Transcripts were analyzed using thematic analysis (Braun & Clarke, 2006). Two researchers independently coded the data, initially indexing segments related to embodied exploration, presence and agency, multimedia cognitive processing, collaborative sense-making, and emotional engagement. Through iterative comparison and discussion, the coding scheme was refined, discrepancies were reconciled, and a final set of six themes was agreed upon—deepened engagement, multi-sensory interaction, knowledge acquisition, conceptual reappraisal, future pedagogical preference, and emotional resonance.

To ensure trustworthiness, we incorporated member checking and ethical safeguards. Participants were invited to review selected transcript excerpts and thematic summaries, confirming that our interpretations accurately reflected their experiences. Collectively, these measures enhanced the credibility, dependability, and ethical integrity of our qualitative inquiry into LBE VR’s educational impact.

6. Findings

All 57 invited students completed the interviews, yielding a 100% response rate and underscoring strong participant engagement with the LBE VR intervention. Quantitative measures revealed that 95% of respondents reported being satisfied or very satisfied with the VR-based pedagogical experience, indicating that the immersive format not only met but often exceeded learners ’expectations. This overwhelmingly positive reception provided a solid foundation for deeper qualitative analysis.

Open-ended responses were subjected to grounded theory–informed thematic analysis (Strauss & Corbin, 1994). Transcripts were segmented into semantically discrete units, typically corresponding to single thought fragments, and independently coded by two researchers. Through iterative rounds of open, axial, and selective coding, we identified six emergent themes—deepened engagement, multi-sensory interaction, knowledge acquisition, conceptual reappraisal, future pedagogical preference, and emotional resonance. The resulting codebook, along with frequency distributions, guided our interpretation of how LBE VR’s theoretical propositions manifested in student experiences.

A clear majority of participants (75%) described a marked increase in engagement during the LBE VR sessions, often using terms such as “immersive,” “captivating,” and “all my senses were activated.” Nearly half of the learners (47%) specifically emphasized the multi-sensory richness of the environment—citing synchronized visuals, spatialized audio, and kinesthetic movement—that made them feel “truly present” in the Peking Man cave. One student noted, “Hearing the sound of fire burning as I walked through the cave made me forget I was in a venue,” capturing how integrated audio-visual design deepens focus and presence.

Every interviewee reported new factual insights into Peking Man’s daily life—ranging from fire-management strategies to stone-tool crafting techniques (e.g., figure 13). Approximately one-third of students went further, describing a critical reappraisal of their preconceptions about prehistoric humans. As one learner reflected, “I always thought Peking Man was primitive, but now I see how resourceful and intelligent they were.” These narratives illustrate how embodied, narrative-driven exploration can both convey concrete knowledge and prompt learners to reconstruct their mental models.

Figure 13. "Making stone tools" virtual teaching.

Looking ahead, 80% of respondents expressed a strong preference for incorporating LBE VR into future history or cultural heritage lessons. Many highlighted how the active, participatory format transformed abstract concepts into tangible experiences: "I remember details better when I'm part of the story," remarked one student. This forward-looking endorsement suggests that emotionally engaging, contextually rich VR designs foster sustained motivation and learner buy-in.

Participants also described several novel teaching scenarios unlocked by LBE VR's affordances. By donning head-mounted displays and entering a virtual Zhoukoudian cave, they could "walk where Peking Man walked," imitating ancient behaviors and intuitively grasping spatial and environmental relationships. Realistic soundscapes—crackling embers, distant animal calls—further enhanced this sense of authenticity. In doing so, learners reported developing a holistic historical framework that wove together geological formations, ecological contexts, and hominin survival strategies, rather than studying each element in isolation.

Crucially, the LBE VR intervention catalyzed a shift from passive reception to active, inquiry-based learning. Students collaborated to define exploration tasks, navigated the VR environment to test hypotheses (e.g., sourcing suitable tinder materials), and consulted embedded resources with instructor support. This cycle of hypothesis, exploration, and reflection not only increased motivation but also fostered critical thinking and creativity. As one participant summarized, "We weren't just watching a video; we were archaeologists uncovering history ourselves."

Finally, learners highlighted how LBE VR addressed common challenges in adolescent education—short attention spans and resistance to lecture-based methods—by transforming specialized subjects into vivid, scenario-based explorations. The blend of "time-travel" immersion and on-site visits to the Locality 1 archaeological site of the Zhoukoudian Peking Man Cave created a multidimensional learning continuum. According to students, this approach significantly boosted interest in human origins and improved retention of factual details, demonstrating LBE VR's potential to maximize the educational value of heritage sites while supporting long-term cultural preservation goals.

7. Conclusion

This study set out to investigate how LBE VR can transform cultural-heritage education through theory-driven design and immersive pedagogical practice. By analyzing the experiences of 57 secondary-school students who engaged with a narrative-driven LBE VR programme of the Zhoukoudian Peking Man site, we demonstrated that LBE VR's core affordances—expansive spatial design, free-roaming interaction, integrated audio-visual modalities, multi-user collaboration, structured storytelling, and contextualized character and venue elements—collectively foster deep cognitive, social, and affective learning outcomes.

Our thematic findings revealed that 75% of learners experienced a pronounced increase in engagement and presence, corroborating the claims about embodied cognition and agency through large-scale, precise tracking environments. Integrated audio-visual design was credited by nearly half of participants with sustaining focus and reducing cognitive load, while narrative-driven structuring and contextualized character and venue design elicited strong emotional resonance and memory retention. Moreover, multi-user interaction was shown to scaffold collaborative inquiry, promote peer learning.

Educationally, the LBE VR intervention shifted students from passive observation to active, inquiry-based roles—defining their own exploration tasks, testing hypotheses in situ, and reflecting on discoveries—which resulted in both substantive knowledge gains and critical reappraisal of preconceived notions about prehistoric human life. Eighty percent of participants expressed a desire to see LBE VR integrated into future curricular contexts, highlighting its potential for sustained adoption in formal and informal learning environments.

While our results underscore the pedagogical promise of LBE VR, practical considerations—such as the technological infrastructure required for large-scale tracking and high-fidelity rendering—must be addressed for broader implementation. Additionally, our study focused on a single heritage site and a relatively homogeneous learner group; future research should examine diverse cultural contexts, age ranges, and learning objectives, as well as conduct controlled comparisons against traditional exhibit modalities to quantify learning gains and long-term retention.

In sum, this research contributes both a conceptual framework and empirical evidence for leveraging LBE VR as a powerful, theory-driven tool in heritage education. By aligning cutting-edge immersive technologies with established learning theories, educators and heritage professionals can create richly engaging, emotionally resonant experiences that bridge past and present, deepen understanding of human origins, and inspire lifelong curiosity about our shared cultural legacy.

References

Braun, Virginia & Clarke, Victoria. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology.* 3. 77-101.

Carrozzino, M., Bergamasco, M., 2010: Beyond virtual museums: Experiencing immersive virtual reality in real museums. *Journal of cultural heritage*, 11(4), 452-458.

Cecotti, H., 2022. A serious game in fully immersive virtual reality for teaching astronomy based on the messier catalog. In *2022 8th International Conference of the Immersive Learning Research Network (iLRN)* (pp. 1-7). IEEE.

Freina L, Ott M. A literature review on immersive virtual reality in education: state of the art and perspectives[C]//The international scientific conference elearning and software for education. 2015, 1(133): 10-1007.

Green, M. C., & Brock, T. C. (2000). The role of transportation in the persuasiveness of public narratives. *Journal of Personality and Social Psychology*, 79(5), 701–721.

Kolb, D. A. (1984). Experiential Learning: Experience as the Source of Learning and Development. *Englewood Cliffs, NJ: Prentice Hall*.

Leite, W. L., Svinicki, M., & Shi, Y., 2010: Attempted validation of the scores of the VARK: Learning styles inventory with multitrait–multimethod confirmatory factor analysis models. *Educational and Psychological Measurement*, 70(2), 323-339.

Slater, M., & Wilbur, S. 1997. A framework for immersive virtual environments (FIVE): Speculations on the role of presence in virtual environments. *Presence: Teleoperators & Virtual Environments*, 6(6), 603-616.

Strauss, A., & Corbin, J. (1994). Grounded theory methodology: An overview. In N. K. Denzin & Y. S. Lincoln (Eds.), *Handbook of qualitative research* (pp. 273–285).