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SCIENTIFIC VIRTUAL REALITY AS A RESEARCH TOOL IN PREHISTORIC ARCHAEOLOGY: THE CASE OF ATXURRA CAVE (NORTHERN SPAIN)

REALIDAD VIRTUAL CIENTÍFICA COMO HERRAMIENTA DE INVESTIGACIÓN EN ARQUEOLOGÍA PREHISTÓRICA: EL CASO DE LA CUEVA DE ATXURRA (NORTE DE ESPAÑA)

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Highlights:

- This study proposes the practical utility of an immersive Virtual Reality (VR) experience for the dissemination and study of Palaeolithic Rock Art.
- Thanks to a series of multidisciplinary studies, a virtual reconstruction of the archaeological context of an area with rock art has been achieved.
- The Palaeolithic lighting systems documented in Atxurra cave have been virtually recreated, allowing real-time interaction through VR.

Abstract:

The Upper Palaeolithic period (ca. 45000 - 12000 BP) was the time when figurative art chiefly produced by *Homo sapiens* emerged and developed. The Upper Palaeolithic rock art entails a multisensory experience that goes beyond depicted images observation: it includes aspects related to the cognitive development of human mind, the spatial dimensions, the type of rock surface, artificial lighting, and challenges of navigating the underground environment. Traditionally, the study of Palaeolithic art in caves has focused on paintings and illustrated subjects' graphic analysis. However, a recent shift in methodological focus has favoured a comprehensive and interdisciplinary study of rock art. This new perspective has allowed the investigation of surrounding elements that significantly influence the art and its interpretation. Combining this with new digital technologies, it is now possible to reconstruct Palaeolithic artistic creation and contemplation environments with precision, offering researchers an immersive and interactive experience through virtual reality (VR). The two documented Palaeolithic lighting systems in the sector J "Ledge of the Horses" have been virtually recreated. The lighting simulation parameters are based on those obtained from an anthracological study of the charcoal remains found in the cave and the subsequent experimental program. The study included analysing both three-dimensional (3D) models of the cave, obtained through photogrammetry and laser scanning, and the lighting systems in the graphics engine ©Unreal Engine 5; this allowed the researchers to create an interactive VR environment that faithfully reflects the current state of scientific knowledge about the cavity. Using VR is a substantial methodological advancement, regarding both knowledge transmission and the creation of more robust and coherent archaeological interpretations through sensory perception and

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historical empathy. This approach has been applied to the main decorated sector of the Atxurra Cave (Basque Country, Spain), a space containing dozens of engraved and painted representations, and surface archaeological material, subjected to a comprehensive multidisciplinary study.

Keywords: virtual reality (VR); virtual archaeology; Upper Palaeolithic; rock art; Palaeolithic lighting

Resumen:

El Paleolítico Superior (ca. 45000 - 12000 BP) fue la época de la aparición y el desarrollo del arte figurativo producido principalmente por el *Homo sapiens*. El arte rupestre del Paleolítico Superior supone una experiencia multisensorial que va más allá de la observación de las imágenes representadas: abarca aspectos relacionados con el desarrollo cognitivo de la mente humana, las dimensiones espaciales, el tipo de superficie rocosa, la iluminación artificial y la dificultad del tránsito por el medio subterráneo. Tradicionalmente, el estudio del arte paleolítico en cuevas se ha centrado en el análisis gráfico de pinturas y temas figurativos. Sin embargo, un reciente cambio de enfoque metodológico ha favorecido un estudio exhaustivo e interdisciplinar del arte rupestre. Esta nueva perspectiva ha permitido investigar elementos del entorno que influyen significativamente en el arte y su interpretación. Combinando esto con las nuevas tecnologías digitales, ahora es posible reconstruir con precisión los entornos de creación y contemplación artística paleolíticos, ofreciendo a quienes investigan una experiencia inmersiva e interactiva a través de la realidad virtual (RV). Se han recreado virtualmente los dos sistemas de iluminación paleolíticos documentados en el sector J "Repisa de los Caballos". Los parámetros de la simulación lumínica se basan en los obtenidos a partir de un estudio antracológico de los restos de carbón hallados en la cueva y el posterior programa experimental. La inclusión de modelos tridimensionales (3D) de la cueva, obtenidos mediante fotogrametría y escaneado láser y de los sistemas de iluminación en el motor gráfico ©Unreal Engine 5, permite la creación de un entorno interactivo de RV que refleja fielmente el estado actual de los conocimientos científicos sobre la cavidad. El uso de la RV representa un avance metodológico sustancial, no sólo para la transmisión de conocimientos, sino también para la creación de interpretaciones arqueológicas más sólidas y coherentes a través de la percepción sensorial y la empatía histórica. Este enfoque se ha aplicado al principal sector decorado de la cueva de Atxurra (País Vasco, España); este espacio contiene decenas de representaciones grabadas y pintadas, así como material arqueológico en superficie, sometido a un exhaustivo estudio multidisciplinar.

Palabras clave: realidad virtual (RV); arqueología virtual; Paleolítico Superior; arte rupestre; iluminación paleolítica

1. Introduction

The Upper Palaeolithic period (ca. 45,000 - 12, 000 BP) was the time of the emergence and development of figurative art, including rock art, produced chiefly by *Homo sapiens* (Lewis-Williams, 2002; Douka & Higham, 2017; Hublin et al, 2020). However, some authors propose that examples of Middle Palaeolithic rock art may have been produced by Neanderthals (Hoffmann et al., 2018). Virtual archaeology and virtual reality can enhance our understanding of the world and circumstances in which the art was created.

The concept of virtual archaeology has been employed since the last decades of the 20th century to refer to the reconstruction or simulation of the prehistorical past through the use of digital technologies. In recent years, there has been a significant technological advance, both in terms of quality and accessibility, driven by the digital revolution primarily experienced by the video game industry.

Virtual reality, augmented reality, and serious games, i.e. video games designed with the purpose of teaching, training, informing, or raising awareness about a specific topic, are emerging as increasingly versatile tools not only for the dissemination of archaeological heritage but also for the generation of historical knowledge. The ability to reconstruct and recreate the past through scientific research endows these media with an excellent capacity to depict various archaeological findings, as well as the possibility of engaging researchers in a historical context in a fully immersive manner, which can aid in formulating new hypotheses.

These techniques have not been applied uniformly to all historical periods, with a greater proliferation of research on virtual architectural reconstructions for classical periods (Banfi, 2020; Ferdani et al., 2020; Egea-Vivancos & Arias-Ferrer, 2021). However, there have also been some virtual reality reconstructions in caves with Palaeolithic art (Barrera & Baeza, 2010; Baeza & Cantalejo, 2013). Nevertheless, the latter focuses on prehistorical outreach, based on the current state of the cave or recreating the prehistoric context with special emphasis on aesthetic matters rather than the rigour of archaeological data, thus obtaining a distorted or non-scientific view of the past.

In this present work, we aim to approach past reality as closely as possible through digital reconstructions of the subterranean environment with a solid scientific foundation. The representation of the karstic environment itself, as well as all the archaeological elements incorporated into the scene, is based on data obtained through a transdisciplinary study (facilitated by the excellent preservation of the archaeological context associated with Palaeolithic art), combining various disciplines such as technical studies of rock art, fire and lighting archaeology, and endokarstic geomorphology, among others. This interdisciplinary and archaeologically compatible approach, coupled with the ability to visualise and interact with the reconstructions through virtual reality viewers, is what we define as Scientific Virtual Reality (SVR).

Recreations of this kind make it possible to analyse Palaeolithic representations under conditions (spatial, lighting, original state of the graphics, etc.) very similar to those found by prehistoric artists. It represents a significant methodological advancement in the study of rock art and decisively contributes to the development of more robust and coherent archaeological interpretations through sensory perception and historical empathy (Weinzierl & Lepa, 2017; Hoffmeister et al., 2016; Hoffmeister, 2017; Jouteau et al., 2020; San Martín & Ortega-Sánchez, 2020; Wisher & Needham, 2023; Wisher et al., 2023).

2. Research aim

Palaeolithic rock art is a form of cultural communication that appears to rely on multiple sensory aspects to convey its message (Hodgson, 2008; Porr, 2010; Dobrez, 2016; Domingo et al., 2016; Feruglio et al., 2019). It is a result of the development of human mind (Mithen, 1996; Lewis-Williams, 2002; Renfrew, 2008a, 2008b). Like other cultural expressions such as theatre or opera, the concept of “the total work of art” may have prevailed, combining different individual art forms to create a complete and immersive artistic experience that engages all the senses (Wagner, 1851). From this perspective, ethnography suggests that rock art requires the convergence of diverse elements to create a complete experience (Díaz-Andreu & Mattioli, 2019; Lahelma, 2010). Aspects such as lighting, sounds, the volume of the rock surface, or the difficulty of access are important for the total understanding of rock art.

However, archaeological evidence offers a partial or sometimes biased view of the phenomenon, including the researchers' own focus, which has sometimes underestimated the interest in this global integrative perspective on rock art as a multisensory experience (Garate, 2007). Although we can never fully recover the original experience, we can strive to approach it through the virtual understanding and simulation of the multisensory aspects of rock art, based on interdisciplinary study.

Traditionally, methods for recording and studying Palaeolithic rock art have focused strictly on graphic motifs, their style, technique, colours or chronological attribution, and to a lesser extent, on the rock surface and immediate context in which they are found, or other evidence of human activity around the art. Therefore, an approach to the artistic phenomenon from more integrative perspectives is deemed necessary, focusing efforts on gaining knowledge about different past activities associated with the creation and contemplation of rock art, as well as the perceptual issues of its creators and audience (de Beaune, 2018). Despite the acknowledgment by different authors of suggestive acoustics in decorated caves (Dauvois & Boutillon, 1990; Utrilla, 1994; Utrilla & Bea, 2008), the use of lighting effects in artistic compositions (de Beaune, 1987; 2018), or the importance of the Internal Archaeological Context

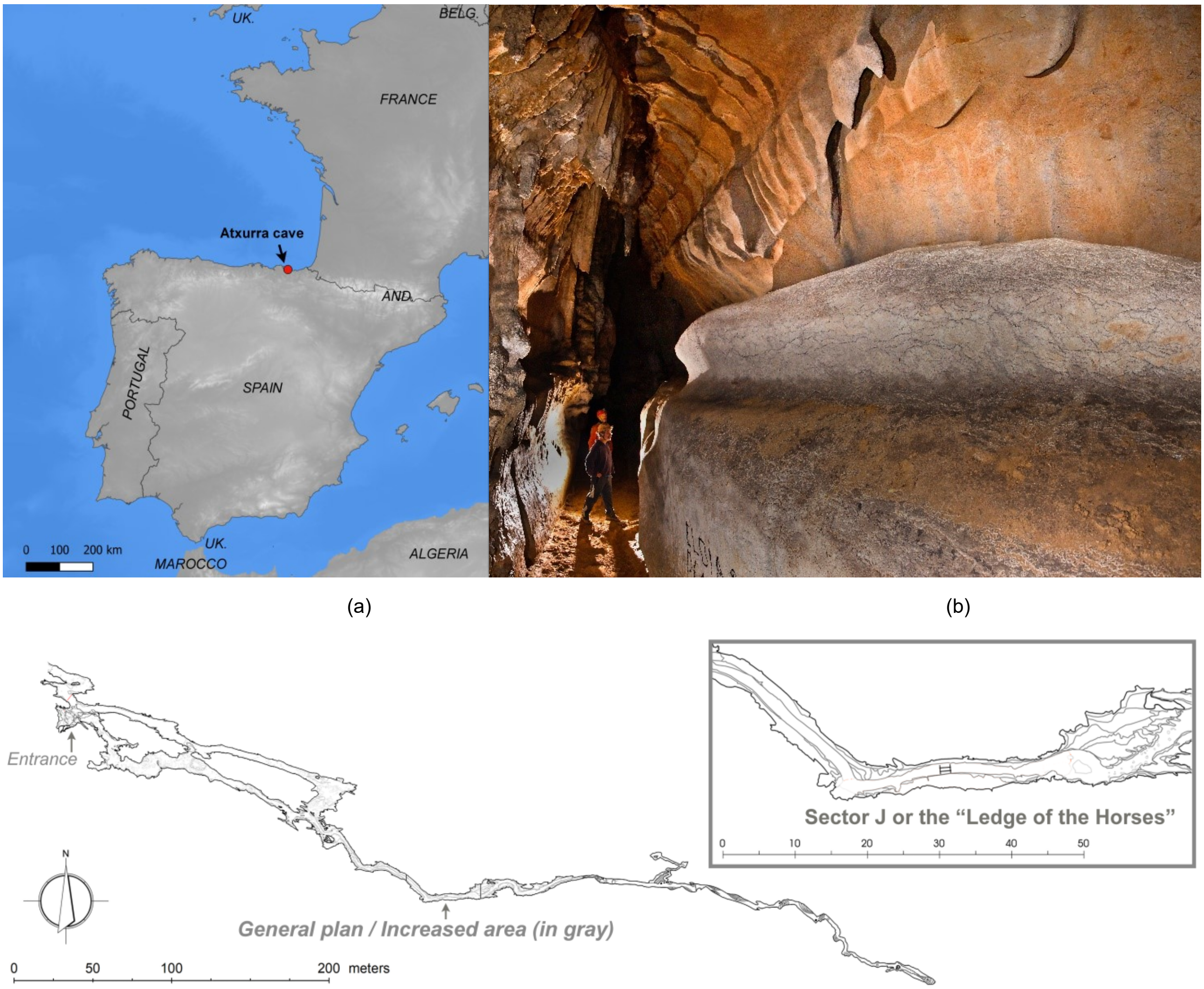

Figure 1: Atxurra Cave: a) Map showing the location of (Source: https://ec.europa.eu); b) Photography of Sector J or the “Ledge of the Horses”, showing its location at the right wall of the passage (X. Gezuraga); and c) Plan of the cave generated from the scanned point cloud (Gim-Geomatics, SL) and caving survey (ADES).

(a) (b)

Figure 2: Examples of before (a) and after (b) virtual restoration of prehistoric glyphs, digitally removing modern graffiti.

(IAC, henceforth) (Clottes, 1993), it has only been in more recent times that a shift has occurred in the approach to studying activities surrounding Palaeolithic rock art, based on quantifiable data (Fazenda et al., 2017; Díaz-Andreu & Mattioli, 2019; Till, 2019; Medina-Alcaide, 2019; Jouteau et al., 2020; Fritz et al., 2021). This shift in research trend pays more attention to information from the context in which graphic manifestations are integrated (Medina-Alcaide et al., 2018), thus allowing the study of the artistic phenomenon in terms of sensory perception, as well as its economic and social implications, and not solely from a stylistic point of view (Garate, 2017; de Beaune, 2018).

Considering the existing archaeological record, cases where we can obtain information about sensory experiences related to Palaeolithic rock art through traditional working methods are rare. However, thanks to the virtual reconstruction of different components of artistic representation based on scientific data (archaeo-acoustic, geomorphological, archaeo-luminous, etc.), it is possible to recreate the physical conditions in which these graphic manifestations took place.

By recreating the multisensory experience of Palaeolithic art, we aim to enhance the exploration of new lines of research at a historical moment when interpretations of the artistic phenomenon seem to be exhausted, and occasionally limited to the quantification and cataloguing of prehistoric graphic motifs.

A particular decorated section of Atxurra Cave (Basque Country, Spain), the "Repisa de los Caballos" (Ledge of the Horses), has been selected to implement these theoretical-methodological approaches. This raised space preserves almost intact floors where elements of IAC associated with Palaeolithic engravings have been found. Additionally, this shelf has been the subject of meticulous interdisciplinary studies addressing the main aspects of geoarchaeological research associated with Palaeolithic art (Garate et al., 2023).

3. Case study: the Atxurra Cave

The cave of Atxurra is a prehistoric site known since 1929 (Barandiarán, 1961). It is formed in Aptian-Albian reef limestone (Lower Cretaceous) that outcrops on the coast in the East Cantabrian region (Northern Spain) (Fig. 1a). The cave consists of two cave-levels, the lower one called Armiña, and the upper one, Atxurra. The entrances are located on the right bank of the Zulueta stream, a tributary of the Lea River that flows into the Cantabrian Sea.

The natural entrance used by prehistoric societies to access the cave system was the upper entrance of Atxurra (Rios-Garaizar et al., 2020; Arriolabengoa et al., 2020). It is currently 35 m above the stream, and it opens in a small hall where an Upper Palaeolithic Gravettian and Magdalenian cultural phases as well as a Bronze Age occupation sequence has been identified (Barandiarán, 1961; Rios-Garaizar et al., 2019). There are two points of union between the two levels, one of them a few meters from the upper-level occupation site and another at the end of the lower-level gallery of Armiña, under the point where the decorated sector begins (Fig. 1b). The upper level, which is the location of the rock art, continues for about 600 m after this second connection (Fig. 1c).

In 2014, the archaeological excavations at the entrance of Atxurra were resumed to assess the potential of the remaining deposit. In 2015, during a systematic survey of the cave walls, D. Garate and I. Intxaurbe found several decorated panels with Magdalenian-style engravings (Garate et al., 2016).

The decorated sectors are between 186 m and 366 m from the prehistoric access and are located mainly on side ledges that can be reached by climbing. In total, there are 22 decorated places in which more than a hundred animals, such as bison, horses, ibex, hinds, and aurochs, have been depicted. All of them are engraved and, in some cases, painted in black. The style and conventions suggest a Late Magdalenian (ca. 14000-15500 cal BP) attribution (Garate et al., 2020). In other parts of the cave a few red stains, perhaps linked to the transit of people stained with ochre, have been also found (Medina-Alcaide et al., 2018). In addition, all the adjacent floors contain archaeological remains (especially lithic tools and charcoal from prehistoric lighting systems) abandoned during different visits in prehistoric times. Also, in the Armiña sector, a brief Late Magdalenian occupation with some lithics (including a probable fire striker), a hearth, and an ochre stain was excavated and interpreted as an inner cave context (Rios-Garaizar et al., 2020).

The virtual reconstruction specifically focuses on Sector J in Atxurra Cave, also known as the "Ledge of the Horses", situated on a raised cornice approximately 3.4 m high on the right wall when facing the entrance of the main gallery (Fig. 1b). An article has recently been published on this area using an interdisciplinary approach, which will serve as our archaeological foundation to lend scientific validity to our virtual recreation (Garate et al., 2023). The adorned side of the cornice measures 12 m in length, with an overall width of 1.2 m, and a useful surface area (with a slope less than 30°) of 33 m^2. It features a panel with Palaeolithic art, incorporating nearly a hundred graphic units, along with various archaeological remains such as lithic industry artefacts, combustion areas, and scattered charcoal remnants from wooden torches on the floor. The sector is 329 m from the cave entrance, and reaching the platform involves climbing an inclined slope at the end of the cornice.

4. Methodology

A holistic and interdisciplinary study approach is necessary to achieve the virtual reconstruction of the multisensory experience of rock art. This starts with the premise that all archaeological remains found at a site, as well as modifications to the underground environment, whether of anthropogenic and/or natural origin, provide relevant information for the study of the artistic phenomenon. Thus, all archaeo-geological data should be subject to study at the same level of importance as the prehistoric graphics themselves.

The workflow involves the identification and collection of archaeological and geological data *in situ*, followed by an interdisciplinary study of these data. Subsequently, specific experimental programs are developed, three-dimensional (3D) documentation of the underground environment is conducted, and finally, all this information is integrated into a graphics engine to create the SVR experience.

4.1. Study of the internal archaeological context (IAC)

The meticulous exploration of the cave in search of any elements comprising the IAC (Clottes, 1993; Garate, 2017; Sanchidrián & Medina-Alcaide, 2017; Medina-Alcaide et al., 2018) constitutes the first step in our workflow. These remains are typically located on the cave floor and exhibit notable fragility, often representing traces of ephemeral and discreet visits to the subterranean environment (Rios-Garaizar et al., 2020). Therefore, during virtualization tasks or research on parietal graphics, it is crucial to prevent current human traffic from approaching undocumented archaeological surfaces to preserve as many of these pieces of evidence from prehistoric visits as possible.

Any element comprising the IAC will contribute relevant information to understand the activities carried out by human groups inside the caves, whether related to the execution or visitation of Palaeolithic rock art.

In this way, archaeological remains such as flint tools used to engrave motifs are closely linked to artistic production. However, other traces, such as charcoal remains, reddened clay, or thermal alterations in the rock, reveal actions that could have been intrinsically related to the artwork, although they may not be as evident at first glance and may be linked to different phases of visitation. This is why all remains found in the site are a potential source of historical information to reconstruct the context of the creation/viewing of Palaeolithic rock art. Moreover, the location of the

Figure 3: Visual synthesis of the virtualisation workflow. From photogrammetry and laser scanning to virtual restoration and lighting, and integration into the graphics engine.

remains (e.g., the placement of hearths), and not just their presence, can provide relevant information about the decisions made by human groups in that artistic creation context (Intxaurbe et al., 2021, 2022; Garate et al., 2023). Thus, their georeferencing and inclusion in Geographic Information Systems (GIS) are of great interest in extracting more precise conclusions about the visibility of the panels, cave traffic, relative chronology of the remains, or post-depositional processes they may have undergone (Intxaurbe et al., 2020).

Furthermore, the charcoal remains found on the Ledge of the Horses in Atxurra Cave were dated through C14-acclerator mass spectrometry (AMS) analysis (Garate et al., 2023) and subjected to anthracological study for taxonomic identification and taphonomic analysis (Medina-Alcaide, 2019). All of this was carried out with the aim of gaining deeper insights into the knowledge of the lighting systems used to access this cave area. The data obtained from these analyses served as a foundation for designing an experimental program that replicates various lighting systems used in Atxurra Cave. In this experimental program, torches, lamps, and fixed fires were simulated using the type of fuel documented during the archaeological study. Parameters such as illuminance (lx), luminous intensity (cd), luminance (cd/m^2), range, temperature reached (ºC), and duration of use of light sources were measured and characterized (Medina-Alcaide et al., 2021).

4.2. Geomorphological study of the subterranean landscape

The subterranean landscape can undergo changes over thousands of years or within a few minutes due to sedimentary and erosive processes. In this regard, it is crucial to identify the different geomorphological and sedimentological features of the cave, subsequently organizing them into stratigraphic units, and establishing a chronological framework for them (e.g., Delannoy et al., 2010; Arriolabengoa et al., 2020; Genuite et al., 2021).

This information is essential for adjusting 3D models and removing elements from the landscape, such as speleothems that did not exist in prehistoric times, altering floor levels, or restoring collapses (Intxaurbe et al., 2023). Ultimately, this brings us closer to the reality of the endokarst frequented by Palaeolithic groups, allowing us to better understand their transit decisions and the various activities, both artistic and otherwise, carried out within the caves (Intxaurbe et al., 2023).

4.3. 3D documentation and wall study

With the aim of obtaining a high-resolution 3D model of the ledge without shadows to facilitate the subsequent addition of virtual lighting, a photogrammetric capture was carried out with flash heads arranged parallel to the photographic camera. Specifically, the photographs were taken using a framework consisting of four flash heads, which, in turn, held a Nikon® D610 full-frame reflex camera with a pixel count of 24.3MP and a Nikkor® AF-S 24-85 mm VR F3.5-4.5G ED lens at 35mm.

In addition, colour management standards were followed to achieve proper colour management in the digital development of images and, consequently, a photogrammetric model with high colour fidelity (Pereira, 2013; Ruiz-López, 2020). These standards include the use of a Colorchecker® Passport colour scale and a development workflow with specialised software (Colorchecker® Passport v. 1.1.1, Adobe Photoshop® v. 2024, and Frame® v. 1.5).

The 3D model was obtained within Agisoft Metashape® Pro v. 1.8.1 software and processed on a Dell® Precision 3630 workstation with an ©Intel Core I9-9900 CPU 3.10GHz 8 cores, 128GB of RAM, and an NVIDIA® GeForce® RTX 2080 graphics card.

In previous work, the cave was virtualised using the terrestrial laser scanner (TLS) Faro® Photon X 20/120, including the area where the Ledge of the Horses is located, as well as the wall study and graphic restitution of the engraved motifs present on the ledge itself (Rivero et al., 2019).

4.4. 3D editing

Corrections to the 3D models were made with free 3D editing software, in our case, Blender® v. 4.0, together with relevant modifications for simulating the original state of the Ledge of the Horses in Atxurra Cave.

Once the 3D model of the ledge with uniform lighting is obtained, the tracings of the engraved figures were projected onto it. This displays how the lines would appear freshly made on the rock surface, with much greater visibility, as it does not have a patina. The high-resolution photogrammetric model of the ledge (ground sampling distance 0.19mm/pix) is also integrated into the 3D model of the gallery whose mesh has been generated with CloudCompare® v. 2.13.1 software using the point cloud obtained with the Terrestrial Laser Scanner. To make the process more agile, the cave was divided into several segments with continuous stations. These were loaded into the software and merged later. Once all the clouds were joined in a single cluster, the points were normalised by triangulation (using the 'scan grids' with the sensor and the same method for the orientation, and with a 'k nearest neighbour' value of six 'minimum spanning tree'). The normalised point cloud was later turned into a mesh with the 'Poisson surface reconstruction' process (with an 'octree depth' of 8, and a mean resolution of 0.05 m) (Kazhdan et al., 2006; Kazhdan & Hoppe, 2013). Finally, the different segments were loaded into the Meshlab® v. 2023.12 programme and joined together; then the geometries in common were cleaned up and any errors were removed. Similarly, the virtual elimination of modern graffiti and engravings on the rock frieze was achieved through texture correction (Fig. 2). The lighting systems used were digitally modelled, replicating the torch and fire formats that yielded the best results during experimentation and aligned with the archaeological evidence documented in Atxurra Cave (Medina-Alcaide et al., 2021).

4.5. Immersive experience in VR

The information generated in the previous sections converges at this point, providing an archaeological foundation for the virtual reconstruction. The graphics engine serves as a container for the 3D models and enables the creation of a virtual environment where it is possible to simulate various physical parameters and interact with different elements in real time. In this sense, a graphics engine or game engine is software that streamlines the production of video games, virtual animation environments, visualization, or simulation. The main objective of a graphics engine is to provide programming routines that allow, among other things, working with 2D and 3D environments, graphic rendering (models, materials, lighting, and shading), control design, user interface, sound management, and integration into VR (Bolognesi & Aiello, 2019; Choromański et al., 2019).

Among the different graphics engines available today, we have chosen to use Unreal Engine® v. 5.3.2. This software is relatively easy to use, as it is based on a node-based command system called Blueprint, which makes the configuration of models, materials, interactions, or lighting much more intuitive, replacing the traditional C++ programming language. Additionally, the graphic power supported by this engine allows high levels of realism and multiple light sources can be run simultaneously through VR. Moreover, the software is licensed free when the project is intended for education and/or research.

As a means of audiovisual output, a Meta® Quest 2 VR headset has been used. These VR glasses feature a Snapdragon XR2 processor, 6GB of RAM, LCD screens with a resolution of 1832x1920 pixels, and a refresh rate of 120 Hz. Although they operate wirelessly, given the graphic demands of our reconstruction for maximum realism, they must be connected via a cable to a high-performance computer to provide all the required graphic power.

The graphic power of Unreal Engine® 5 is utilized to realistically simulate the different lighting systems identified on the Ledge of the Horses. The fixed lighting points and the initial point of the mobile torch are located exactly where charcoal remains and rubefaction zones were found during the archaeological survey and excavation (Garate et al., 2023). Additionally, to draw conclusive information about the role of lighting in the execution and/or viewing of rock art, the parameters used in virtual lighting are based on the average values obtained during the previous experimental program (Medina-Alcaide et al., 2021) (Table 1).

5. Results

The ultimate outcome of applying the workflow has been the creation of an immersive SVR experience depicting the context of the creation/observation of rock art on the Ledge of the Horses in Atxurra Cave. This virtual recreation relies on archaeological and experimental data gathered from previous investigations conducted in the cave, ensuring the fidelity of the elements and conditions portrayed in the experience.

5.1. 3D model with integrated tracings

The photogrammetric model of the ledge, obtained from 985 photographs, boasts submillimetre geometric precision and a photorealistic 32K texture, enhancing the observer's sense of realism. Upon this 3D model devoid of shadows, to enhance the implementation of virtual lighting, tracings of the engraved figures (Garate et al., 2023) have been overlaid using a specific methodology (Rivero et al., 2019). These tracings are displayed in a whitish colour, simulating the appearance of recently drawn engravings still devoid of the patina that currently covers them. Additionally, through digital editing of the 3D model's texture, graffiti and modern engravings have been removed to simulate the cave morphology during the Palaeolithic (Arriolabengoa et al., 2020).

5.2. Virtual lightning

Given the idiosyncrasy of underground rock art, light plays a fundamental role in all aspects, from the most practical to the most artistic (de Beaune, 2000). It is the primary element that enables movement through a cave, significantly influencing the execution and observation of graphic manifestations, and thus, the sensory perception of the same. To replicate lighting conditions in the prehistoric era, a simulation of the lighting systems used during the Palaeolithic has been conducted, based on previous studies analysing charcoal remains and areas of reddening documented during surface survey and excavation on the Ledge of the Horses (Garate et al., 2023).

For this purpose, using the Unreal Engine® software, particle systems using Niagara blueprints have been created to simulate the flame of fires and torches, allowing for the modification of multiple attributes. Some adjustable properties include luminous intensity, light flickering, emitted smoke quantity, generated ashes, and flame speed, among others.

Table 1: Lighting values from experimentation with torches and fireplaces (Medina-Alcaide *et al*., 2021).

Lighting type	*Torches*						*Fireplace*
Number of the experiment	**1**	**2**	**3**	**4**	**5**	**$\bar{X}$**	**8**
Max. duration (')	31	19	44	50	61	41	>30
Average E (lux)	19.08	12	9.98	21.61	21.94	16.92	19.20
Average I (cd)	3.05	1.92	1.60	3.46	3.51	2.71	3.07
Average Radius (m.)	2.93	3.20	3.60	2.73	2.47	2.99	3.30
Average L (cd/m2)	2.43	1.53	1.27	2.75	2.79	2.16	2.45
Average High Temperature. Centre (˚C)	537.80	307.25	662.25	666.25	633.88	561.44	586.67
Average High Temperature. Periphery (˚C)	128.60	35.00	58.20	63.88	277.50	112.64	45.00

Figure 4: View of the real-time experience in SVR with using interactive torch lighting.

The first recreated lighting system is a torch (Fig. 4), corresponding to a small portion of reddened clay juxtaposed with charcoal remains found during the archaeological excavation of the ledge. Its small size and elongated shape (8.6 cm x 2.6 cm) suggest its use as a support for a torch or the combustion of a detached fragment from it. The torch becomes an interactive element for the viewer, as the VR user can hold and move it while traversing the ledge, thereby varying the environmental lighting in real time. This allows us to experience the actual visibility provided by the lighting systems used by the artists who decorated the cave of Atxurra.

Similarly, the hearths responsible for the three areas with the presence of reddened clay and the concentration of wood charcoal found during the excavation of the ledge have been recreated (Fig. 5). The depicted wooden branches as fuel correspond to information extracted from the archaeological charcoal, revealing the wood species used as well as their thickness (Medina-Alcaide, 2019).

In this way, it is possible to visualize the context of creation and/or visualization of rock art with two different lighting systems, which, in turn, align with the two phases of frequentation attested through microsedimentology and charcoal dating using C14-AMS (Garate et al., 2023). Additionally, this study reaffirms the conclusions drawn through GIS about the use of fixed fires in the cave of Atxurra as a theatrical element (Appia, 1921; 1954), positioned in a specific manner to correctly illuminate the engravings and allow them to be visible from a specific location (Intxaurbe et al., 2020; Garate et al., 2023).

5.3. SVR experience

All the aforementioned processes lead to the enjoyment of an immersive experience in SVR, where the user can interact with the virtual historical environment. This virtual historical environment incorporates real-time sensory and interactive data that individuals experience and interpret to generate new historical knowledge (Weinzierl & Lepa, 2017). This virtual scenario is confined to the traversable area of the Ledge of the Horses, allowing the user to physically move along it within the space established in reality or through a virtual teleportation system. To achieve a more immersive sensation, realistic physics and collisions provided by the ©Unreal Engine game engine have been utilized, ensuring that the viewer's movements and perspective are responsive to their actions. In this way, the user must adopt the same bodily posture as in the original site to navigate or view the prehistoric motifs, as the 3D model is scaled, and the height of the VR headset is set at 1.60 m, coinciding with the average height of the population in the Upper Palaeolithic (Holt, 2003). In addition, spectators will enjoy an auditory experience, with the recreation of the spatial sound of the flaming torch and fires. Moreover, the user can interact in real-time with various elements in the environment, such as lighting systems or flint tools found on the ledge, using the controls on the VR headset[1].

Ultimately, the user is provided with a fully immersive experience that faithfully recreates the sensation of being physically present on the Ledge of the Horses while adding the incentive of being able to see not only the current state of the cave but also its condition during

[1]The video comparing torch experimentation and the SVR experience can be viewed at the following link: https://youtu.be/CsCcLOAZaD4?si=8eXwPKWM1shjpOLb

the Upper Palaeolithic based on archaeological findings. Thus, virtual models cease to represent the classic three dimensions to include one more—the dimension of time.

6. Discussion

The results obtained in this study demonstrate the technical feasibility of creating an SVR experience for archaeological study and for disseminating the results derived from the analysis of the contexts of Palaeolithic rock art creation.

Conducting a transdisciplinary study of each decorated cave is shown to be an essential requirement for successfully carrying out this type of virtual reconstruction. Thus, the historical reliability of the reconstruction (modelling uncertainty) (Weinzierl & Lepa, 2017) in SVR is directly related to the availability of archaeological remains and the execution of exhaustive studies that allow us to obtain the maximum amount of historical information possible. Through a visualization layer using a colour scale, the user can visually identify the degree of historical-archaeological certainty associated with each represented element, with a specific colour assigned to each level (Aparicio & Figueiredo, 2017).

The simulation of lighting inside caves with Palaeolithic rock art has traditionally been approached using 3D editing software and offline rendering. However, the use of a graphic engine and real-time computing offers several advantages that make this technique very interesting. Firstly, the interactivity provided by the graphic engine allows the user to make adjustments and see the results simultaneously, greatly facilitating the design process and avoiding the need for long rendering times. Additionally, the option to visualise the simulation in real-time enables the user to experiment with different scenarios and lighting conditions, which can be very useful for the research and analysis of the Palaeolithic artistic experience and how lighting affects the perception of motifs (Pettitt et al., 2017; Sakamoto et al., 2020; Rodríguez-González et al., 2023; Wisher & Needham, 2023).

The possibility of achieving greater realism in virtual simulation depends to a large extent on the processing power of the computer and graphic engine used, as well as the resolution and refresh rate of the VR headset. In this sense, software and hardware updates in the field of VR and game development are constant. These improvements are allowing the latest versions of Unreal Engine® to use high-resolution photogrammetric models, resulting in better performance with real-time lighting and a greater sense of realism. Additionally, new VR headset models continuously improve screen resolution, colour representation, and refresh rate, representing a continuous advancement in graphical quality.

In this regard, it is important to highlight some of the ongoing improvements that we plan to implement in future virtual reconstructions. We are currently focusing on characterizing the refractive indices of materials present in the underground environment, as this information will have a direct impact on the accuracy of our lighting simulations (Joteau et al., 2019). Likewise, for acoustic simulations, it is necessary to characterize the absorption and dispersion coefficients of all surfaces (Weinzierl & Lepa, 2017).

Experiences in SVR possess the capability of constant updating, not only due to the continuous improvements in software and hardware mentioned but also because of the possibility of incorporating new archaeological findings. Thus, it becomes a dynamic, adaptive tool in continuous evolution.

With all this, we believe that our project not only presents a solid scientific and technological foundation but also aligns with a line of work with promising prospects and significant applications in the fields of research, education, and heritage dissemination.

7. Conclusions

The ultimate goal of Prehistory or Prehistoric Sciences is the reconstruction and understanding of human societies predating written periods. Traditionally, the knowledge generated has been stored and transmitted through written documentation and drawings or illustrations. In recent years, new technologies have introduced innovative information transmission systems, allowing for virtual reconstruction based on scientific data.

As the limitations of conveying the spatial sensation of underground environments through photographs or other conventional means became evident, and 3D virtualization techniques proliferated, the format of paper publications—or their digital counterpart—became obsolete. Thus, the creation and dissemination of scientifically-based VR environments depicting sites with Palaeolithic rock art could enhance remote understanding and study. This aligns directly with the principles of open science and its impact on society and the economy proposed by the European program Horizon Europe.

Simultaneously, VR can be employed as a tool for archaeological research, enabling researchers to spatially position themselves in front of a rock art panel comfortably and for an unlimited duration, a feat not always achievable due to conservation restrictions or accessibility challenges. Furthermore, this virtual recreation can include tracings of the figures, display the motifs based on their execution sequence, different texture viewing options (DStretch, ultraviolet, or infrared), or real-time simulation of prehistoric lighting, providing historical information regarding endokarst transit viability or visibility of rock art panels (Intxaurbe et al., 2020, 2021; Medina-Alcaide et al., 2021; Monteith et al., 2022; Wisher & Needham, 2023).

In this context, our work has focused on exploring the possibilities offered by SVR as a platform for the research and dissemination of decorated Upper Palaeolithic caves. We applied this technique specifically to the Ledge of the Horses in Atxurra Cave, as this location meets the necessary requirements for a virtual reproduction of the Palaeolithic scenario, including a preliminary study of geomorphology, existing rock art, and prehistoric lighting systems used in the cave.

To achieve this, it is essential to conduct a multidisciplinary analysis that compiles all the necessary information to simulate a specific moment in the past with maximum accuracy. Additionally, experimental programs in an endokarstic context must be carried out, simulating the original conditions to complement archaeological information and define the array of variables that could have influenced each site, providing crucial data for the simulation of lighting systems.

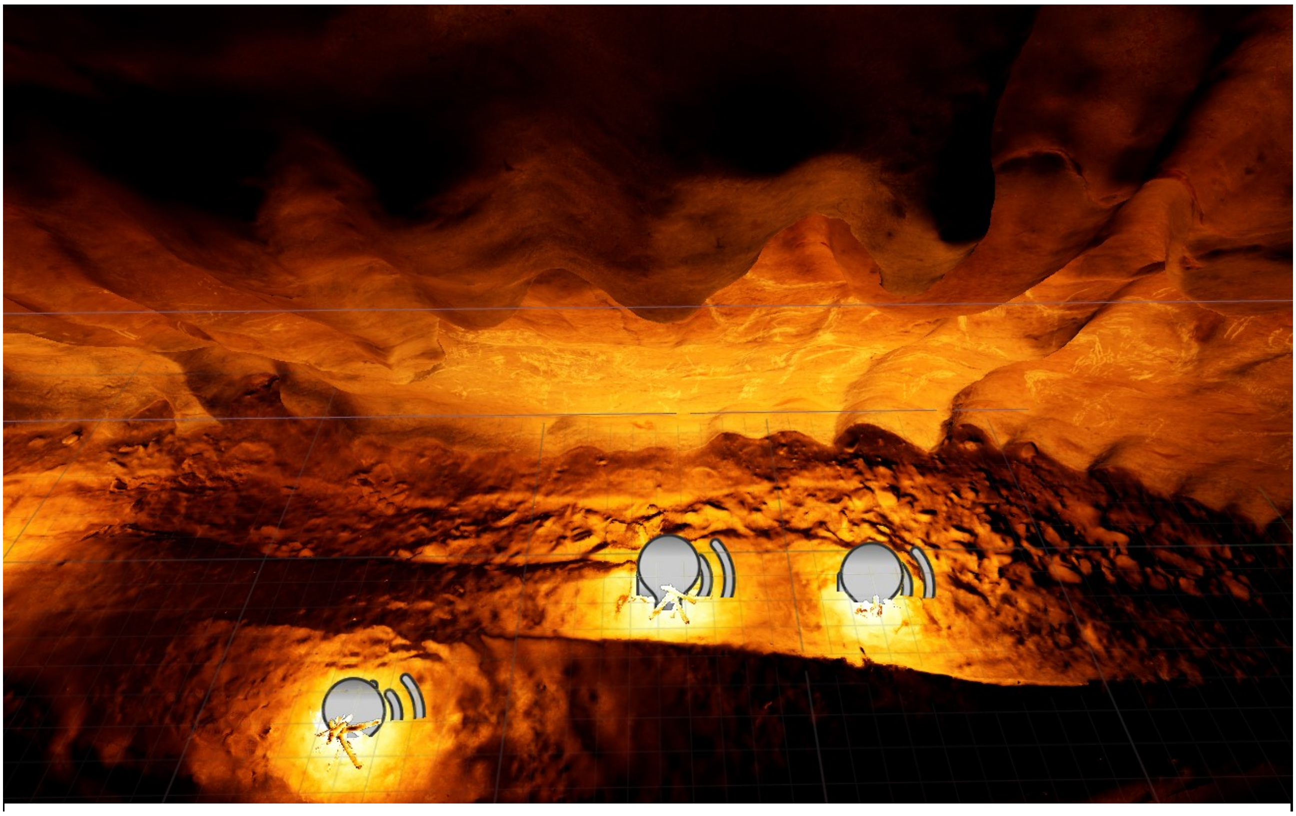

Figure 5: View of the graphic engine with the arrangement of the fixed fires on the ledge.

SVR has allowed us to reconstruct what the creation and/or observation scenario of Palaeolithic rock art in underground settings was like at a specific point in time. In this way, the ability to modify a large number of parameters and observe prehistoric engravings in their original state can promote *sympathy* (Moro-Abadia, 2009) with Palaeolithic artists and, consequently, the formulation of new hypotheses by researchers.

This work leads into a new avenue of research that simultaneously provides versatile visual support for scientific information and allows interaction between the researcher and the virtual historical environment. In other words, SVR is not limited to generating a final product that may seem more or less faithful and aesthetically pleasing; it is about creating a tool that allows the researcher to delve into their study through the recreation itself. This product is also dynamic since both advances in research and technological improvements enable constant updates to progress toward historical knowledge that is as accurate as possible.

SVR presents itself as a high-quality scientific dissemination platform, containing the latest archaeological theories about a site, and as a means to offer public access to restricted environments, whether due to conservation, accessibility, or physical limitations. All this with the advantage of adapting content to the target audience through the narrative of virtual simulation, facilitating the understanding of historical information through gamification of learning (Wei et al., 2023; Rodríguez-González et al., 2023; Bideci & Bideci, 2023).

In summary, the ability to virtually recreate (pre)historic scenarios based on scientific data not only represents a path towards high-quality scientific dissemination but also serves as a tool or platform for researchers to present and share the conclusions of their studies and generate new historical knowledge.

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