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Illuminating palaeolithic art using virtual reality: A new method for integrating dynamic firelight into interpretations of art production and use

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ABSTRACT

Approaches to Palaeolithic art have increasingly shifted beyond the traditional focus on engraved or depicted forms in isolation, to appreciating the sensorial experience of art making as integral to shaping the form of depictions and the meaning imbued within them. This kind of research appreciates an array of factors pertinent to how the art may have been understood or experienced by people during the Palaeolithic, including placement, lighting, accessibility, sound, and tactility. This paper contributes to this "sensory turn" in Palaeolithic art research, arguing that the roving light cast by the naked flame of fires, torches or lamps is an important dimension in understanding artistic experiences. However, capturing these effects, whether during analysis, as part of interpretation, or presentation, can be challenging. A new method is presented in virtual reality (VR) modelling – applied to Palaeolithic art contexts for the first time - as a safe and non-destructive means of simulating dynamic light sources to facilitate analysis, interpretation, and presentation of Palaeolithic art under actualistic lighting conditions. VR was applied to two Magdalenian case studies: parietal art from Las Monedas (Spain) and portable stone plaquettes from Montastruc (France). VR models were produced using Unity software and digital models of the art captured via whitelight (Montastruc) and photogrammetric (Las Monedas) scans. The results demonstrate that this novel application of VR facilitates the testing of hypotheses related to the sensorial and experiential dimensions of Palaeolithic art, allowing discussions of these elements to be elevated beyond theoretical ideas.

1. Introduction

In recent years, interpretations of Upper Palaeolithic art have shifted towards a nuanced appreciation of sensorial and experiential elements of production and use, with a deeper consideration of the role of cave topographies, acoustics, tactility and other elements (e.g., Fazenda et al., 2017; Jouteau et al., 2020; Pettitt et al., 2014; Sakamoto et al., 2020). Within this "sensory turn", lighting systems have also been considered as a means to animate depicted forms (Azéma and Rivère, 2012) or even induce hypoxia and altered states of consciousness (Kedar et al., 2021; Lewis-Williams, 1997; Lewis-Williams, 2004). Whilst these conceptual perspectives appreciate fire beyond its quotidian applications in Palaeolithic lifeways, methodological approaches often cast fire and its light as a pragmatic technology in artistic contexts, used as a matter of necessity in the absence of daylight. In this sense, fire is perceived as passive within the process of art making. This paper advances an alternative position, that fire was a technology whose properties actively shaped the artist's sensory engagements with their art. Shifting focus to fire and its light as active agents in this way can expand understanding of how art was made, used, and experienced within particular contexts.

The argument is advanced in two parts. In Part 1, a theoretical framework is developed to reconsider the role of firelight, building from anthropological and psychological research. Anthropological accounts of the role of fire within social and cosmological settings are considered, revealing a rich array of applications that blur the 'functional' and 'nonfunctional' spheres. Making and using art by firelight is revealed to be a particularly charged and potent activity within certain cosmologies. Visual psychology and neurological responses to firelight are evaluated, revealing that the warm, dim, flickering, red-shifted light that fire produces can have significant impacts on the human visual system in a

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range of contexts. These perspectives tangibly evidence how firelight shapes social and cultural interactions, and significantly impacts experience and sensation, inviting a deeper consideration of how firelight actively influenced the making and reception of Palaeolithic art.

However, this raises a potential challenge: in practical terms, how can art be investigated using dynamic lighting conditions when it is not feasible to use fire, torch, or lamp light within art-bearing caves or museum collections? In Part 2, a new digital method in Virtual Reality (VR) modelling is presented as an essential tool for addressing this issue. By utilising VR models built using insights derived from an archaeological context, the visual effects of firelight can be integrated and evaluated systematically. A full methodology for using VR modelling in Palaeolithic art research is presented and two case study applications of the technique - the first of their kind within a Palaeolithic context - are discussed. The role of firelight in the selection of materials and surfaces to paint or engrave and in enhancing depictions to augment depth and movement, is explored through the models produced. The wider significance of fire and its light in art contexts is discussed, alongside consideration of VR as a method to facilitate evidence-led assessments of dynamic lighting within diverse periods.

2. Part 1: New theoretical perspectives on fire and its light

2.1. The sensorial and experiential in Palaeolithic art

Approaches to Palaeolithic art have become increasingly diverse, with a movement away from focusing on the completed form as a locus of meaning, and towards an incorporation of the wider context in which art was made and experienced, especially in caves. Sensory factors - such as tactility (Pettitt et al., 2014); darkness (Pettitt 2016; Pettitt et al., 2017; Sakamoto et al., 2020); and acoustics (Fazenda et al., 2017; Jouteau et al., 2020; Reznikoff 2014; Till 2014; Waller 2019) – and contextual factors – such as the relationship between art placement and space (Intxaurbe et al., 2020; Jouteau et al., 2019; Pettitt et al., 2017; Robert 2016; Sakamoto et al., 2020), or interactions between engraving/painting and rock surface (Bahn, 2003; Clottes 2013; Hodgson & Pettitt 2018; Pastoors & Weniger 2011; Pettitt 2016) – have been explored, drawing attention to their importance in art production and use. This approach has also seen application to portable art contexts, including consideration of the integration of support form into engraved or painted animal motifs (Conneller, 2011; Farbstein, 2013; Needham, 2017; Needham et al., 2022), the role of movement (Azéma and Rivère, 2012), and production and use in darkness (Arias, 2009).

This shift has advanced in tandem with an expanding methodological toolset which allows for the analysis of art in increasing detail, including a range of 2.5D and 3D modelling methods (Domingo et al., 2013; García Moreno and Garate, 2015; González-Aguilera et al., 2009; Güth, 2012; Lerma et al., 2010; Mudge et al., 2006; Plisson and Zotkina, 2015); digital imaging approaches, such as DStretch (Defrasne, 2014; Harman, 2008; Le Quellec et al., 2015; Man-Estier et al., 2015; Quesada and Harman, 2019); diverse types of microscopy (Bello et al., 2017; Bello et al., 2020; Fritz, 1999; Fritz and Tosello, 2007; Marshack, 1972), and experimental approaches (Alvarez et al., 2001; Ferrier et al., 2014; Salmon et al., 2021; Rivero and Garate, 2020). The exploration of wider contextual factors together with new methods has proved to be a powerful way to approach art and advance understanding. However, current methods do not facilitate the consideration of all aspects of art contexts.

A crucial, but underexplored, aspect of art making is the presence of fire and its light. Fire was of fundamental importance during Upper Palaeolithic life, and its quotidian uses are well attested, including extending the day (Pettitt et al., 2017); cooking (Kabukcu et al., 2022; Nakazawa et al., 2009); heating water (Nakazawa et al., 2009); providing warmth (Kedar et al., 2020); heat treating materials (Cavallo et al., 2018; Moník et al., 2017; Perlès and Vanhaeren, 2010), and creating synthetics (Bradtmöller et al., 2016; Cnuts et al., 2018). However, less attention has been given to the potential for fire to play a more-than-functional role in Palaeolithic art contexts. Discussions of lighting technologies have tended to gravitate to the functional, including: the identification of lighting methods (fixed fires, lamps, torches) (Garate et al., 2020); experimental approaches to understand the properties of firelight cast from different types of lamps or torches (de Beaune, 1987; de Beaune and White, 1993; Medina-Alcaide et al., 2015; Medina-Alcaide et al., 2021); and the extent to which particular lighting systems and the materials they were made from were sufficient to illuminate art panels (Ferrier et al., 2014; Medina-Alcaide et al., 2019). Whilst this contributes significant insight into the context of art making through the preparation of appropriate lighting technologies, firelight remains passive: a practical means of illuminating art in the absence of daylight.

2.2. Insights from anthropology

A more active conceptualisation of fire and firelight in Palaeolithic art contexts has begun to emerge, notably surrounding the "animation" of animal depictions (Azéma, 2021; Azéma and Rivère, 2012) and the deliberate exploding or fragmenting of portable art (Arias, 2009; Bahn, 2014; Tosello, 2003, 2005; Rivero, 2012; Vandiver et al., 1989), in part inspired by anthropological observations of active engagements with art through performance. Previous archaeological studies have also used analogies with the anthropological record to understand Palaeolithic fire from a functional perspective linked to making, management and use (Mallol and Henry, 2017; McCauley et al., 2020; Scherjon et al., 2015). However, this reflects only a facet of documented contemporary hunter-gatherer engagements with fire, and accounts exploring its role in the social, cultural and cosmological contexts are less developed. Across diverse contemporary hunting and gathering communities, fire has a wide array of documented social applications, including socialising, telling stories, and dancing. Anderson (2006, 8-9) reports that for the Orochen Evenkis (Siberia), the fireside is an important centre of activity where people gathered to carry out practical tasks, such as repairs or eating, but also to smoke and socialise. Both Wiessner (2014) and Marshall (1961, 252) discuss Ju/'hoansi (Namibia) use of fire as an important social space where people congregate during visits and when telling stories, especially at night. In a wider cross-cultural review, Sugiyama and Reilly (2023) documented 31 cultures that utilised the fireside as a locus for storytelling. The fireside can also be a performance space. Finnegan (2013) notes that the Yaka (Democratic Republic of Congo) and Mbuti (Democratic Republic of Congo) perform ceremonies involving dance by the fireside, while Marshall (1969, 357) documents fireside medicine dances amongst the Ju/'hoansi (Namibia), with the fire contributing to performers entering trance states.

Fire can also feature prominently within cosmological systems. Gould's (1971) analysis of fire use amongst eastern desert Aborigines (Australia) documents a diverse suite of functional applications, but also its role within storytelling of The Dreaming, as well as the performance of ceremonies at night, both for warmth and light, and as an active agent within rituals. Page et al. (2018, 46) reports the use of fire in promoting good health amongst the Agta (Philippines), where it is kept burning during childbirth to keep away cold winds that harbour evil spirits. For the Evenk (Siberia), fire is an element of the upper world and the hearth is a means of communicating with this realm and with the spirits of the deceased (Grøn et al., 2008, 65-66). Hearths can also be home to spirits and on certain occasions fires were fed food in thanks, such as after a successful hunt, or when returning to camp at a previously occupied location (Grøn et al., 2008, 66). Fire is thus more than a passive backdrop around which socially or cosmologically charged activities happen; instead, it is an active component of them.

The active nature of fire can be seen clearly within some documented accounts of art production and use. Polychromatic paintings made by the Ju/'hoansi on rock shelters have been argued to have their cosmological power magnified in the presence of firelight, which serves to

augment the realism of depictions and enhance the perception of movement (Mazel, 2021, 11), as well as increase vibrancy and three-dimensionality (Lewis-Williams and Dowson, 1990, 12). Firelight in such accounts actively shapes perception and experience of art, rendering it more dynamic. This effect is reported to activate the human visual system regardless of the angle of the light (Mazel, 2021, 10), suggesting that any type of firelight could promote this effect.

Fire and light emerge as important agents in sociality and cosmology. In some contexts, firelight is a prominent and vibrant aspect of how art was experienced and understood, and through its particular effects served to enhance the social and cosmological power of depictions. However, it is not clear from the anthropological literature alone why fire and its light can have such powerful effects on human societies. Consideration of how the human visual system processes firelight, and how it can shape perception and experience, can provide further insight into why it holds such importance within hunter-gatherer communities – past and present – and how it produces such powerful effects when viewing art.

2.3. *Insights from visual psychology*

Visual and perceptual psychology offers an important means of understanding the sensorial effects of firelight, both in the contemporary world and in the past, including in relation to art production and use. Previous archaeological applications have included discussion of pareidolic- or hyper- imagery elicited by darkness in caves (Hodgson, 2003,2006,2008,2012,2021); the suggestion that cave environments potentially induced altered states of consciousness (Lewis-Williams 1997, 2004; Lewis-Williams and Clottes, 1998; Lewis-Williams and Dowson, 1988); the testing of psychologically-derived hypotheses related to the overrepresentation of salient animal features in open-air rock art (Meyering et al., 2020); and consideration of how visual responses such as pareidolia were activated by firelight, informing the making and use of some portable (Needham 2017; Needham et al., 2022) and parietal (Wisher, 2022; Wisher et al., forthcoming) art. However, consideration of the precise visual and perceptual effects firelight evokes using psychology, and how these effects may have manifested or been intentionally harnessed within artistic behaviours, is needed.

Whilst there has been limited discussion of firelight in the psychological literature, its fundamental properties - unpredictable flickering light and shadow; warm and dim light of approximately 1900 K; red-shifting of colour - have each been explored in other contexts and their perceptual effects are well understood. The visual system uses cues from light and shadow to process depth, dimensions, shape perception, and movement of objects in the world (Proulx, 2014). This likely stems from processing objects illuminated by daylight, which provides a constant when perceiving a scene, augmented by shadows which give reliable information about an object (Snowden et al., 2006). The manipulation of these conditions, for example by introducing moving or false shadows, elicits particular sensory responses, such as an object appearing as if in motion or changes to size relative to true dimensions (Imura et al., 2006; Imura et al., 2008; Katsuyama et al., 2011; Kersten et al. 1996; Mamassian et al. 1998). Similar perceptual effects may be elicited by the shifting shadows produced by objects illuminated by firelight, whether from fires, torches, or lamps. Shadows cast by firelight will flicker and move unpredictably, particularly when illuminating morphologically complex stone supports used in some art making, eliciting similar illusory responses of perceiving movement in depicted forms. Additionally, the relative brightness of the firelight would activate the cone (bright light adapted) cells in the eye and bleach rod (dim light adapted) cells, preventing the eye from fully adjusting to darkness (Snowden et al., 2006). This may cause visual stimuli in the darkness to be even more ambiguous, slowly being distinguished if paid visual attention for a prolonged period of time but disappearing as the eye saccades back to areas illuminated by firelight.

Low light conditions also evoke particular psychological effects, with objects being processed holistically based on general form rather than individual features, inducing a construal level effect (Steidle et al., 2011; Steidle et al., 2013). Construal level pertains to the psychological distance (temporal, spatial, social, hypotheticality) of an object or event and whether it is considered in a concrete or abstract way (Steidle et al., 2011). Under dim light, as objects are processed more holistically by the visual system, construal level is heightened, increasing the perception of objects in abstract ways and elevating creativity (Steidle and Werth 2013; Zmigrod et al., 2015). Producing art under dim light conditions may thus encourage the abstraction of both topographic features of the cave wall or support - manifesting, for example, as a pareidolic response to such features - and the depictions themselves, with greater attention paid to general form (i.e., salient outline) than individual details as construal level and holistic processing are heightened.

The warm, red-shifted nature of firelight stimulates the visual system and promotes collegiality, cooperation, social connection and social behaviours by creating an atmosphere conducive to the extension of self to include others (Baron et al. 1992; Kombeiz et al., 2017). In contemporary settings, such lighting has been used to encourage conflict resolution, with people more likely to openly share their emotional response to an issue and work empathetically and collaboratively to resolve it (Kombeiz et al., 2017). Warm-light can also red-shift colours in the environment, exciting the visual system which can stimulate an emotional response and encourage creativity (Kombeiz and Steidle 2018). In comparison to daylight, which is homogenous, cool-toned light of approx. 6500 K, firelight evokes creative and emotional responses and encourages intimate, social behaviours.

These psychological effects also emphasise how the properties of firelight can *actively* affect vision, perception and even social interactions, perhaps providing insight into why fire is prominent in some socially and cosmologically charged contexts amongst contemporary hunting and gathering communities. In Palaeolithic contexts, the creativity and heightened sense of social interaction and group cohesiveness that firelight can stimulate may have been an important dimension of art production and reception, and the wider suite of practices surrounding it. The properties of firelight, such as its shifting and dynamic nature, may have been desirable, powerful, and actively harnessed in such contexts, inducing visceral visual illusions, animating motifs by making them appear as if in movement, or enlivening rock and inspiring the placement of depictions. The development of a practical method that facilitates an evidence-led modelling of lighting conditions for specific Palaeolithic art corpora is therefore fundamental, with clear potential to expand understanding of how art was perceived and experienced.

3. Part 2: Using virtual Reality modelling to enhance art analysis and interpretation

Part 1 demonstrated that fire is an active agent within a breadth of contemporary hunter-gatherer social, cultural and cosmological contexts, enriching the experience. Visual psychology provided deeper insight, showing that fire and its light can activate aspects of visual perception, shaping sensation in these contexts of use. The properties of fire have universal effects on the visual system, inducing a sense of movement and dynamism in objects illuminated by its flickering light, which can influence creativity and sociality. The dynamic effects of firelight - whether in caves or more open contexts at night - was a core part of engagement in Palaeolithic artistic practices, being foundational to experience and sensation during production and use, and its capture is important to facilitate interpretation. In Part 2, Virtual Reality (VR) modelling is introduced as a practical solution for systematically analysing, from an emic perspective, the dynamic visual and perceptual effects of firelight in particular art contexts.

3.1. Modelling dynamic light and the advantages of VR

Attempts to utilise digital techniques to simulate the lighting effects of lamps, torches or fires for Palaeolithic art are rare. Chalmers (2002) reflects an early attempt to simulate the interaction of dynamic lighting in relation to an art panel using a suite of computer-vision methods and 2D images extracted from a laser-scan of the art. Although Chalmers (2002) stressed the importance of simulating the visual effects of fire-light for Palaeolithic art, attempts remain infrequent. Subsequent approaches have used software such as 3D Studio Max or Blender (García and Castillejo, 2015; Hoffmeister, 2017) or software such as PHANIE that simulates light based on spectral data (Jouteau et al., 2020). Whilst these softwares are useful in facilitating intuitive simulations that input and manipulate real-world lighting data, they are limited to considering the extent of illumination afforded by a particular lighting technology as a static model, and are only capable of manipulating 3D models at low resolutions. In a Palaeolithic art context this may compromise the simulation with subtle undulations, texture such as cracks or fissures, and even finely engraved depictions, not appropriately captured within the model. VR software such as Unity - a free and accessible game-development software - offers a solution. Unity can simulate the real-time effects of a flickering light source using high-resolution 3D models. It can also create additional 3D objects (or "assets") that can be coded to have particular qualities; manipulate lighting to provide ambient light conditions or lighting from a certain source; code light sources to add pertinent attributes such as irregular flicker and colour temperature; and simulate real-world interactions between modelled and 3D objects. Consequently, access to high-resolution data is important when populating VR models, such as experimental data regarding the exact colour temperature and range of illumination provided by a particular lighting technology.

3.2. Materials: Targeted sites and protocol used

VR dynamic light simulations were modelled for Palaeolithic art from two Magdalenian sites (Needham et al., 2022; Wisher et al., forthcoming): a series of charcoal drawn parietal animal depictions from within the limestone cave of Las Monedas (Spain), with AMS radiocarbon dates of 13,766–13,248 cal. B.P. and 14,811–13,791 cal. B.P. obtained from ibex 16, and 14,076–13,519 cal. B.P. from horse 20 (García-Diez et al., 2021; Moure Romanillo et al., 1996); and portable engraved animal depictions on limestone plaquettes from the rock-shelter site of Montastruc (France), dating to 12070 ± 180B.P. (14587–13579 cal. B.P.) and 13020 ± 130 BP (15980–15220 cal. B.P.) (Cook, 2010). The simulation results - the first of their kind in a Palaeolithic context - are used to evaluate the efficacy of the technique in contributing to new interpretations.

3.2.1. Las Monedas

The art of Las Monedas – consisting of 30 figurative and 15 non-figurative depictions drawn in charcoal – is constrained within one small gallery (Gallery of the Paintings, approximately 5 m × 20 m) of the large cave, leaving many suitable cave surfaces unused (Ochoa, 2017; Ripoll Perello, 1980). The placement of depictions appears intentional and work was carried out to understand the factors that shaped selection (Wisher, 2022; Wisher et al., forthcoming). The interplay between dynamic cave topography and firelight - a requirement in a dark cave environment - may have been significant in influencing art placement, perhaps to achieve particular visual effects. A VR simulation was created to test this (Wisher, 2022; Wisher et al., forthcoming).

For the Las Monedas simulation (Wisher, 2022), photogrammetric models of the majority of the cave walls were imported into a virtual environment constructed in Unity, with 28 of the 30 figurative depictions analysed within the VR simulations. Non-figurative motifs were not considered as these primarily consist of small traces or lines and, as early Medieval radiocarbon dates have been obtained from some non-figurative marks (García-Diez et al., 2021), it is less certain that these motifs can be confidently attributed to the Upper Palaeolithic. As the art in Las Monedas is situated beyond the reach of daylight (Ochoa, 2017), ambient light was set to near absolute darkness in the model. No evidence for lamps or fires has been recovered from Las Monedas, suggesting torches were the likely method of illumination. A torch asset was produced and a point light was used to simulate torch light in the model to capture this. This emits light in all directions equally with an intensity inversely proportional to the distance from the centre of the light source, capturing how light behaves in the real world. Based on experimental

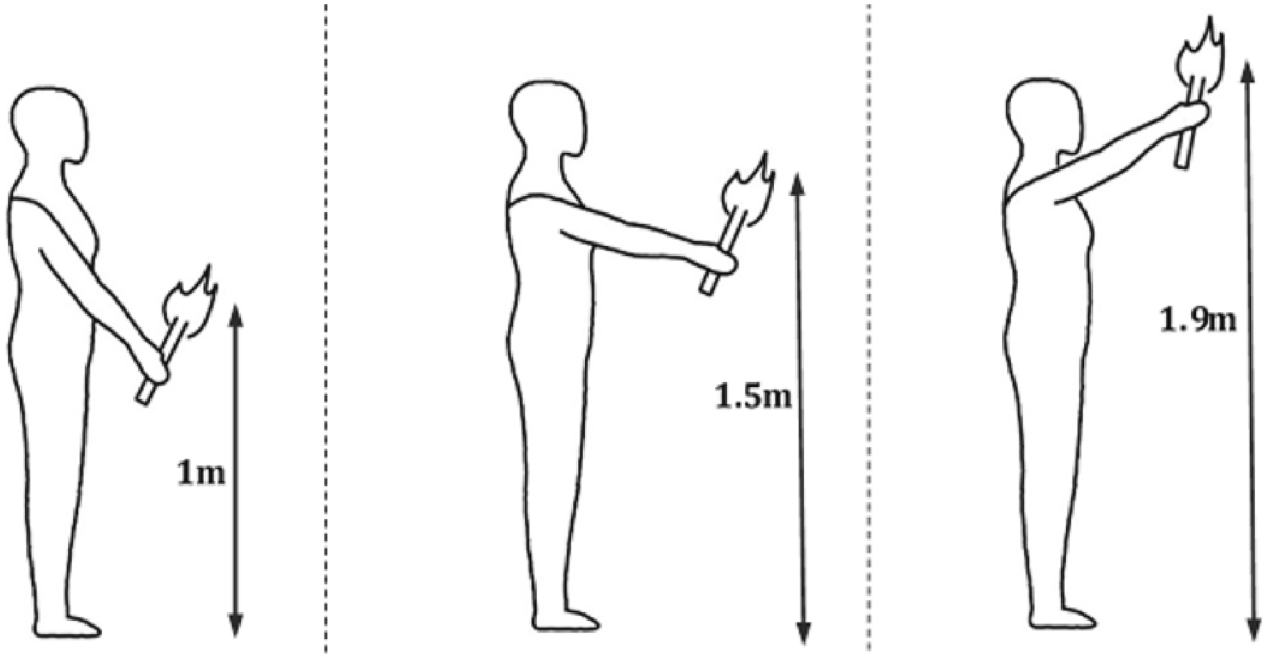

Fig. 1. Different positions of the virtual torch. Heights correspond to the approximate distance between the floor and the centre of the light source, when the torch is held in different positions.

results for juniper wood torches (Medina-Alcaide et al., 2021), the point light was given a radius of 1.25 m, a temperature of 1900 K, and an arbitrary value of 0.5 for the light intensity. To capture the dynamic nature of firelight, the point light was coded with a C# script to randomly vary light intensity within a set range of +/- 0.25, creating a flickering effect. In Unity, the light intensity values do not correspond to real-world lux values. However, as consideration of dynamic lighting was the objective, specific light intensity values were not essential and the ranges selected were insufficient to create distortion (overlighting/underlighting). The virtual torch was placed at 1 m, 1.5 m and 1.9 m, approximately adult hip, shoulder and head height, to simulate different lighting angles corresponding to the height of a depiction (e.g., a depiction 1.1 m height from the cave floor would have lighting simulated at hip height) (Fig. 1). As there are no torch or rubefaction marks on the cave walls at Las Monedas, lighting distance was modelled consistently at 40 cm, approximately a half-arm length, which is close enough to illuminate the cave wall but without flames coming into direct contact with its surface.

3.2.2. Montastruc

The Montastruc plaquettes - consisting of 54 objects in total, with 50 produced on limestone and 4 with unknown geology - feature naturalistic depictions, including individual and multiple animals, the latter sometimes blurred by the recycling of body elements. Approximately half of the plaquettes (27 in total) evidence rubefaction traces or thermal fragmentation, indicating interaction with a heat source. It was hypothesised that these features were connected and firelight may have been harnessed to create dynamic visual effects across engraved and sometimes morphologically complex limestone surfaces when viewed at night. This research question was addressed with experimental archaeology and 3D modelling, using the results to populate a VR simulation (Needham et al., 2022).

For the Montastruc simulation, a subsample of plaquettes with clear rubefaction traces were selected for the VR analysis, to visualise the experimental observations on the archaeological objects themselves (Needham et al., 2022). A preliminary step was required prior to importing models into Unity. The plaquettes are eroded, with little colour contrast between engravings and the surrounding limestone, but experiments show that fresh engraving was a vibrant white colouration (Needham et al., 2022). Substance Painter was used to recolour engraved lines on 3D models of the plaquettes created by Needham (2017) to capture this effect. The modified 3D models were then imported into an open environment in Unity with ambient light set to near darkness, to capture the visual effects of plaquettes observed by firelight at night (Needham et al., 2022). Spatial relationships between plaquettes and other site features are compromised at Montastruc due to the excavation methods used (Needham 2017). However, rubefaction traces localised to some plaquette edges suggest a direct relationship with fire, likely a hearth (Needham et al., 2022). A small hearth asset was produced with an arbitrary footprint of 0.5 m in diameter, a point light source of 2.5 m radius, a temperature of 1900 K light intensity of value of 0.8. Based on experimental results (Medina-Alcaide et al., 2021; Needham et al., 2022), the light source was also attributed with the C# script that allowed the light intensity to fluctuate within a range of +/- 0.25. In contrast to the Las Monedas simulation, the hearth asset remained static and the plaquette models were positioned around it. To ensure accurate placement of the plaquettes models, orientation was informed by experimental observations with edges modified by rubefaction placed closest to the hearth feature (Needham et al., 2022). The VR simulation allowed for the integration of experimental results directly with the archaeological objects to understand the visual effects of placing the Montastruc plaquettes in proximity to flickering light. No quantitative data were measured from these depictions, as they intended only to visualise the experimental results for the archaeological objects, but screen-capture videos were produced to record the visual effects created by the virtual firelight.

4. Results of VR simulations

4.1. Las Monedas

The Las Monedas simulations of torchlight enabled a deeper consideration of the relationship between placement of depictions and topographic features of the cave wall (Wisher et al., forthcoming). VR revealed, in some cases, a more nuanced interplay between the positioning of depictions and the visual effects of firelight interacting with the rock surface than could be discerned by field or 3D models alone. Different lighting angles appeared to make no appreciable difference to the relationship between firelight, the rock surface, and the depictions. If a depiction was illuminated from below shadows stretched subtly upwards and equally, if illuminated from above, shadows stretched downwards, but the areas of illumination and shadow across a depiction remained broadly consistent. Depictions spatially positioned either very high or low on the cave wall were the exception, where lower or higher angles of light respectively were insufficient to illuminate them.

The majority of figurative depictions (71%) at Las Monedas integrated cave topography to directly represent anatomical features or influence the form of the depiction (Wisher et al., forthcoming). The VR simulations suggest this may have been a direct result of perceiving cave walls under firelight, which facilitated the identification of evocative animal forms embedded within their undulating surfaces and encouraged the manipulation of light and shadow to add drama to the depictions. For example, depiction 5 (Fig. 2) - a bison in vertical orientation - appears to be influenced by firelight coalescing with the cave topography, with the curved edge of the rock surface and subtle cracks in the wall enhanced under firelight and integrated to represent anatomical features. The depiction also harnesses shadows created by firelight, in this case to ambiguate. The flickering and shifting shadows cast by firelight adds dimensionality and depth, creating a subtle impression of movement, while the choice to infill the head of the bison

Fig. 2. Digital tracing (top) and VR simulation (bottom) of Depiction 5.

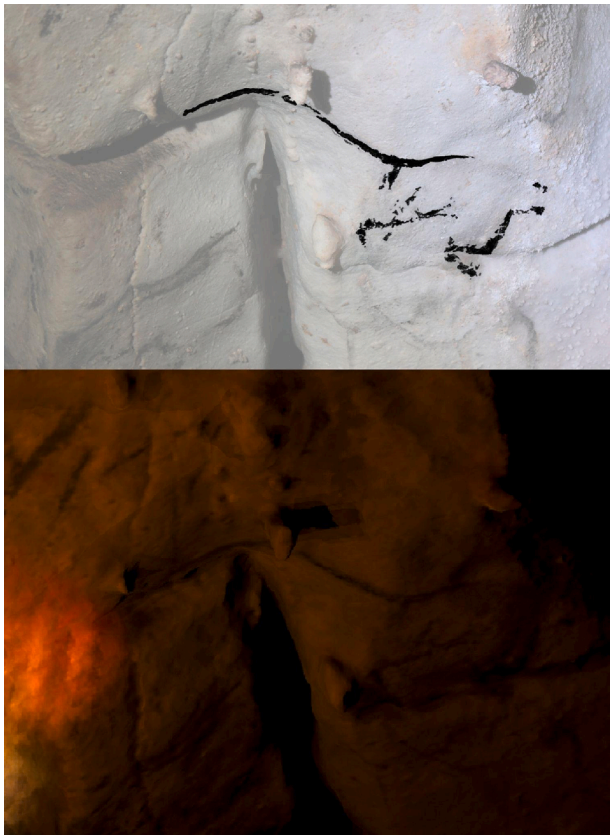

Fig. 3. Digital tracing (top) and VR simulation (bottom) of Depiction 8.

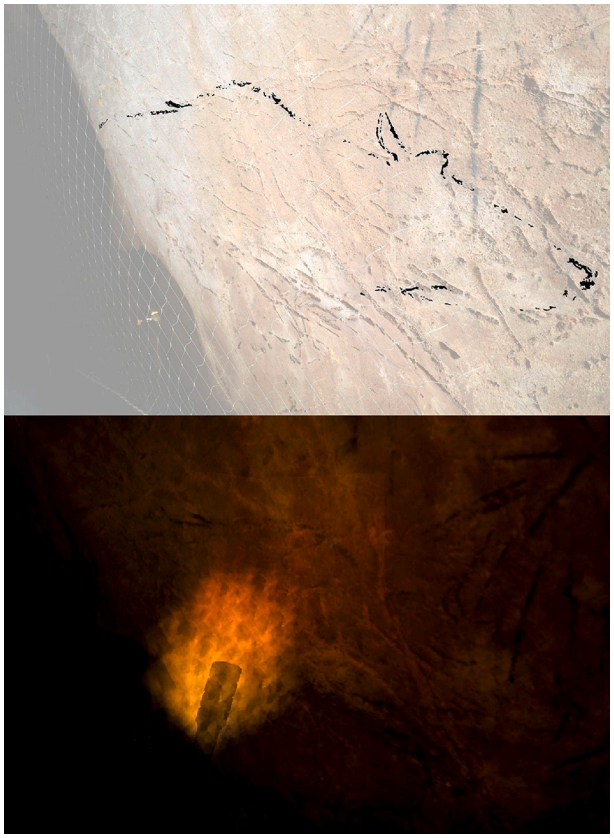

Fig. 4. Digital tracing (top) and VR simulation (bottom) of Depiction 25.

with black pigment blurred the boundary between depiction and shadow, drawing the bison back into the cave surface. The VR simulation for depiction 8 (Fig. 3) - a partial horse in right profile - revealed that a deep, curved crack in the cave wall was enhanced under firelight and directly integrated to represent the dorsal line of the horse. The simulation also indicated that the artist used areas of shadow created by firelight alongside natural cracks and fissures in the cave wall to create the impression of the horse springing from an area of darkness and retreating into another. Firelight in tandem with cave morphology was actively harnessed in art placement, orientation, and form to create a narrative and a sense of movement. Depiction 25 (Fig. 4) - a bear in right profile - appears to have been similarly placed to utilise a subtle concavity, making the animal appear as if it were emerging from the shadows. Again, firelight and cave morphology were integrated to create a powerful visual effect, imbuing the bear with narrative and movement. These insights are only afforded through VR simulations.

The interaction between firelight and the cave surface appears to have been a strongly motivating factor in art production at Las Monedas, perhaps because of the visceral sensory experiences this can create. The VR simulations demonstrate how firelight enhanced cave wall topography by extending shadows cast by cracks or fissures and through fluctuating luminosity across each surface.

4.2. Montastruc

The Montastruc VR simulations allowed for the consideration of experimentally observed phenomena applied to the archaeological objects. This afforded the capacity to explore why particular plaquettes may have been placed adjacent to a hearth, providing insight into the relationship between firelight and the making and experience of plaquettes.

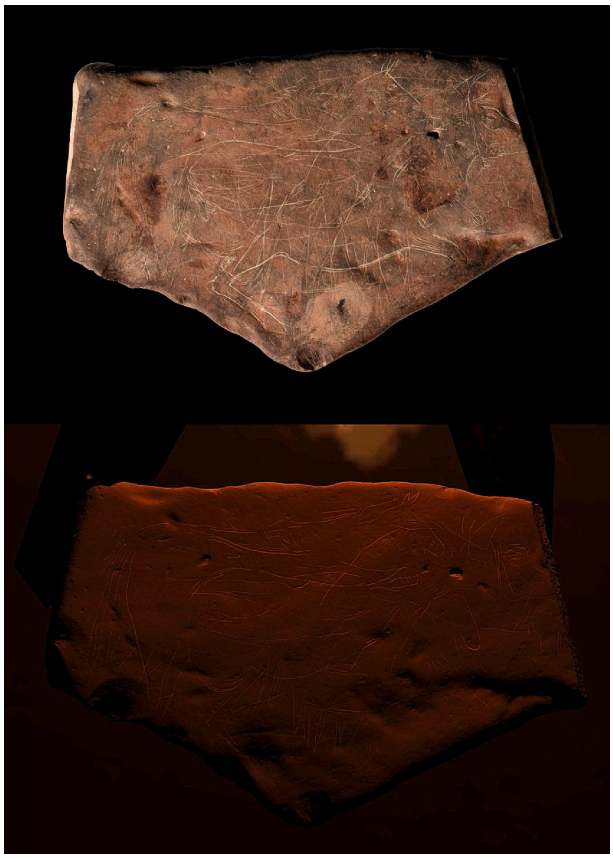

Fig. 5. High resolution image (top) and VR simulation (bottom) of plaquette 691.

The simulations indicated several different visual phenomena elicited by the dynamic firelight. The first pertains to a subtle animation effect when superimposed animal forms were exposed to flickering light. This effect was evident in the simulation of plaquette 691 - featuring multiple horses and a cervid in right profile - where animals appeared to drift in and out of perception as the light shifted (Fig. 5; see Needham et al., 2022 for VR simulation video). The repetition and superimposition may have been designed to harness this perceptual effect of firelight, perhaps evoking a sense of narrative as the animals became animated and appeared to move. This relationship between hearth, light, and portable engraved art encourages deeper considerations of how plaquettes may have been entwined with other social and cultural behaviours that may have been centred around the fireside, such as performance or storytelling.

Another visual effect drawn out by the simulated firelight pertains to artistic choices surrounding the integration of natural features of the limestone into engraved animal depictions. Plaquette 675 - a horse and bovid in right profile - features a horse with cervico-dorsal line fitted to the edge of the limestone support and with the body projecting forwards to allow for the incorporation of a prominent fissure to form part of the front legs. While this artistic choice can be observed with the naked eye (Needham, 2017), the VR simulation shows how in the presence of darkness and flickering light, natural features and anthropogenic engravings blur, creating a powerful visual effect (Fig. 6). Under such conditions, visceral pareidolic experiences can be triggered, which may have contributed to how choices were made in the placement of animals on supports and how they were subsequently experienced and understood.

Finally, a number of plaquettes feature animal depictions that are blended together by recycling body parts and shifting orientations and body postures to fit around existing animals. Plaquette 675 is again a good example, with features of the previously described horse being recycled to create a larger depiction of a bovid. The head of the horse was used to form the ear of the bovid and the abdomen of the horse made up a part of the cervico-dorsal line of the bovid. In what is perhaps a conceptual parallel to the incorporation of natural features of the rock into depictions, the potential existing animal forms created were used as inspiration when adding further engravings. This ambiguity and blending is magnified when viewed under moving firelight in the VR simulation, perhaps enhancing the desired effect of blurring depictions together, but also highlighting the role of firelight in making.

Fig. 6. High resolution image with digital tracing of engraved horse (white) and bovid (grey) (top) and VR simulation (bottom) of plaquette 675.

5. Discussion and conclusion: VR as a method for modelling dynamic lighting in art contexts

Through the novel application of VR, firelight can be understood to have been an active agent in the making and perception of Upper Palaeolithic portable and parietal art that was deliberately harnessed to enrich experience and sensation during engagement. Beyond merely illuminating depictions in the absence of daylight, firelight *transforms* them, imbuing a sense of narrative as animals appear to become animate or move in and out of the shadows. Firelight may have thus been understood as a relational agent intrinsic to the making of art and how it was intended to be engaged with and perceived. The ability to manipulate and harness firelight would have affected the interaction or "conversation" between artist, stone support (cave wall, plaquette), and animal subject, with firelight enabling suitable surfaces to be identified, revealing evocative forms embedded within certain surfaces, and imbuing the depictions produced with narrative. In this sense, fire allowed Palaeolithic artists to "see" twice. Firelight practically functioned to allow people to see at night or within the dark recesses of deeper caves, facilitating the extension of the day or the navigation of complex cave systems. However, firelight also actively enabled a way of seeing that permeated through facets of art making and reception. Firelight allowed artists to engage in new dialogues with stone, by enhancing the evocative topographic forms of the surface to be finished with pigment or engraved lines and by casting dynamic light and shadow that enriched animal forms with movement.

The application of VR modelling to the cave art of Las Monedas and the plaquettes of Montastruc demonstrates its potential for revealing sensorial aspects of dynamic firelight, and enriching interpretations of the active role of fire within the making of Palaeolithic art. The VR simulations allowed for these aspects of firelight to be appreciated and interpreted in a qualitative but systematic way, facilitating insights into the experiential and relational processes involved in art making and perception. As illuminated by Part 1, firelight in contemporary societies is often embedded with practices of storytelling and social interactions by the fireside, and the results for the Montastruc VR simulations suggest this may have been one way the plaquettes were used at this site. The simulations revealed that under dynamic firelight, the superimposed animal engravings appear to be subtly animated. The deliberate association of the plaquettes with firelight indicates that the engravings were made to be seen under firelight, with the dynamic effects of the light manipulating the perception of animal forms through the shadows cast by the limestone's undulating topography and the shifting illumination of vibrant white engraved lines, creating a sense of narrative. It is plausible that this intentional engagement with firelight was part of storytelling in a social space around the fireside. The focus on depicting animals, the use of limestone derived from the rockshelter itself, and the diverse authorship of the engravings suggests such storytelling sat within practices that emphasised place, community participation, and engagements with other-than-human beings (Needham, 2017). By contrast, the constrained spatial context of the Las Monedas art suggests a more intimate interaction between a very limited number of artists, firelight, the cave wall and the depicted animals. The VR simulations revealed the deliberate placement of depictions in relation to areas of shadow at Las Monedas, and the blurring of natural and anthropogenic

elements under firelight, with the charcoal black lines and shading becoming difficult to distinguish from natural features of the cave wall (e.g., cracks, fissures). The high proportion of depictions at Las Monedas that integrate natural topographic features that, when viewed under firelight, induced pareidolic responses (Wisher, 2022; Wisher et al., forthcoming) further reflects this intimate interaction. As illuminated by VR, therefore, the artists appear to have had a dialogical relationship with the cave wall, coaxing out or blurring in animal forms that become embedded in its surface, through a nuanced interplay between light and shadow. This contrasts with the socially-charged context of the Montastruc art; interactions at Las Monedas were more discreet.

This research demonstrates that VR is an important tool that can be constructively used alongside more established techniques in Palaeolithic art research. Where tracings or relevés allow for the particular depiction on a surface to be clearly visualised or the sequence of lines to be determined (Fritz and Tosello, 2007) and 3D models allow for an appreciation of the dimensionality of the art (García Moreno and Garate, 2015; González-Aguilera et al., 2009; Güth, 2012; Lerma et al., 2010), VR can facilitate the appreciation of the role of firelight in transforming and enriching Palaeolithic art. The Las Monedas and Montastruc VR models were built directly from high-resolution 3D models and experimental data, which facilitated the creation of a sub-mm accurate and data-led simulation of the interaction of firelight on different art types and in different contexts. This capacity to integrate multiple strands of data into VR enables rigorous investigation of research questions regarding intangible aspects of Palaeolithic art making and reception, such as sensorial and visual experience. There is vast potential for integrating VR simulations into future research both in Palaeolithic art, and to other contexts where moving light has been raised as a variable in art production and use (Abrams, 2021; Ahola and Lassila, 2022; Nyland and Stebergløkken, 2020). Importantly, VR can consider these intimate and contextual considerations without posing any risk to the archaeology itself, solving a critical issue in the appropriate lighting of archaeological objects.

This application is the first of its kind in Palaeolithic art contexts and inevitably as VR develops, more refined models can be produced that capitalise on advances in hardware and software. For example, Unity offers a High Definition Rendering Pipeline (HDRP) that allows for additional real-world lighting values (e.g., lux) to be modelled. Whilst this currently requires high computing power, particularly to render real-time lighting effects on high resolution 3D models, it demonstrates that new developments will facilitate increasingly refined models in future. The integration of further archaeological and experimental data is another pathway to improving the VR models produced. For example, the light generated by a flame can vary depending on variables such as the fuel used (Chalmers, 2002). As research into Palaeolithic fire expands, including variations in hearth configurations (Murphree and Aldeias, 2022) and fuels used (Aldeias, 2017; Beresford-Jones et al., 2010; Marquer et al., 2010; Théry-Parisot et al., 2005), further experimental results used to understand the properties of particular combinations (Hoare, 2020) can help to create more detailed VR models in future, in turn providing greater specificity and nuance in the light simulation produced. While this paper has focussed on the analytical applications of VR, there is a clear scope for significant application of the technique in the realm of engagement with wider audiences. This offers the exciting potential to show how cave art and some portable art may have been seen from the perspective of those people who made and used it.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data described in the manuscript is published in full in Needham et al., 2022 and Wisher et al. forthcoming.

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Declarations of Interest

None.

References

Abrams, J.J., 2021. Ancient Chinese cave paintings as cinema: the volcanos and dragons of Mogao Cave 249. Int. Commun. Chin. Culture 8 (2), 289–316.

Ahola, M., Lassila, K., 2022. Mesolithic shadow play? Exploring the performative attributes of a zoomorphic wild reindeer (*Rangifer tarandus*) antler artefacts from Finland. Time and Mind: J. Archaeol. Conscious. Culture 15 (2), 167–185.

Aldeias, V., 2017. Experimental approaches to archaeological fire features and their behavioural relevance. Curr. Anthropol. 58, S191–S205.

Alvarez, M., Fiore, D., Favret, E., Castillo Guerra, R., 2001. The use of lithic artefacts for making rock art engravings: observation and analysis of use-wear traces in experimental tools through optical microscopy and SEM. J. Archaeol. Sci. 28 (5), 457–464.

Anderson, D.G., 2006. Dwellings, storage and summer site structure among siberian orochen evenkis: hunter-gatherer vernacular architecture under post-socialist conditions. Nor. Archaeol. Rev. 39 (1), 1–26.

Arias, P., 2009. Rites in the dark? An evaluation of the current evidence for ritual areas at Magdalenian cave sites. World Archaeol. 41 (2), 262–294.

Azéma, M., 2021. Prehistoric cave art: from image to graphic narration. Paragraph 44 (3), 379–393.

Azéma, M., Rivère, F., 2012. Animation in Palaeolithic art: a pre-echo of cinema. Antiquity 86 (332), 316–324.

Bahn, P.G., 2003. Location, location: What can the positioning of cave and rock art reveal about Ice Age motivations? In: Pastoors, A., Weniger, G.C. (Eds.), Höhlenkunst und Raum: Archäologische und architektonische Perspektiven. Neanderthal Museum, Germany, pp. 11–20.

Bahn, P., 2014. Religion and ritual in the upper palaeolithic. In: Cummings, V., Jordan, V. P., Zvelebil, M. (Eds.) The Oxford Handbook of the Archaeology and

Anthropology of Hunter-Gatherers. doi 10.1093/oxfordhb/9780199232444.013.0023.
Baron, R.A., Rea, M.S., Daniels, S.G., 1992. Effects of indoor lighting (illuminance and spectral distribution) on the performance of cognitive tasks and interpersonal behaviors: the potential mediating role of positive affect. Motiv. Emot. 16, 1–33.
Bello, S., Wallduck, R., Parfitt, S.A., Stringer, C.B., 2017. An Upper Palaeolithic engraved human bone associated with ritualistic cannibalism. PLoS One 12 (8), 0183127.
Bello, S., Blinkhorn, E., Needham, A., Bates, M., Duffy, S., Little, A., Pope, M., Scott, B., Shaw, A., Welch, M.D., Kinnaird, T., Millar, L., Robinson, R., Conneller, C., 2020. Artists on the edge of the world: An integrated approach to the study of Magdalenian engraved stone plaquettes from Jersey (Channel Islands). PLoS One 15 (8), e0236875.
Beresford-Jones, D.G., Johnson, K., Pullen, A.G., Pryor, A.J.E., Svoboda, J., Jones, M.K., 2010. Burning wood or burning bone? A reconsideration of flotation evidence from Upper Palaeolithic (Gravettian) sites in the Moravian Corridor. J. Archaeol. Sci. 37, 2799–2811.
Bradtmöller, M., Sarmiento, A., Perales, U., Zuluaga, M.C., 2016. Investigation of Upper Palaeolithic adhesive residues from Cueva Morín, Northern Spain. J. Archaeol. Sci. Reports 7, 1–13.
Cavallo, G., Fontana, F., Gialanella, S., Gonzato, F., Riccardi, M.P., Zorzin, R., Peresani, M., 2018. Heat Treatment of Mineral Pigment during the Upper Palaeolithic in North-East Italy. Archaeometry 60 (5), 1045–1061.
Chalmers, A., 2002. Very realistic graphics for visualising archaeological site reconstructions. In: Proceedings of the 18th Spring Conference on Computer Graphics April 2002, 7–12. New York: Association for Computer Machinery.
Clottes, J., 2013. Why did they draw in those caves? Time and Mind: J. Archaeol. Conscious. Culture 6 (1), 7–14.
Conneller, C., 2011. An Archaeology of Materials: Substantial Transformations in Early Prehistoric Europe. Routledge, London.
Cook, J., 2010. The Swimming Reindeer: Object in Focus. British Museum Press, UK.
Cnuts, D., Tomasso, S., Rots, V., 2018. The Role of Fire in the Life of an Adhesive. J. Archaeol. Method Theory 25, 839–862.
de Beaune, S., 1987. Palaeolithic Lamps and the Specialization: A Hypothesis. Bull. Primitive Technol. 23, 60–67.
de Beaune, S., White, R., 1993. Ice age lamps. Sci. Am. 268, 108–114.
Defrasne, C., 2014. Digital image enhancement for recording rupestrian engravings: applications to an alpine rockshelter. J. Archaeol. Sci. 50, 31–38.
Domingo, I., Villaverde, V., López-Montalvo, E., Lerma, J.L., Cabrelles, M., 2013. Latest developments in rock art recording: towards a integral documentation of Levantine rock art sites combining 2D and 3D recording techniques. J. Archaeol. Sci. 40, 1879–1889.
Farbstein, R., 2013. The materiality of production: exploring variability and choice in the production of palaeolithic portable art made in antler and bone. In: Choyke, A., O'Connor, S. (Eds.), From These Bare Bones: Raw material and the study of worked osseous objects. Oxbow Books, Oxford, pp. 98–108.
Fazenda, B., Scarre, C., Till, R., Pasalodos, R.J., Guerra, M.R., Tejedor, C., Ontañón Peredo, R., Watson, A., Wyatt, S., García Benito, C., Drinkall, H., Foulds, F., 2017. Cave acoustics in prehistory: Exploring the association of Palaeolithic visual motifs and acoustic response. J. Acoust. Soc. Am. 142, 1332–1349.
Ferrier, C., Debard, E., Kervazo, B., Brodard, A., Guibert, P., Baffier, D., Feruglio, V., Gély, B., Geneste, J.-M., Maksud, F., 2014. Heated walls of the cave Chauvet-Pont d'Arc (Ardèche, France): characterization and chronology. Paleo 25, 59–78.
Finnegan, M., 2013. The politics of Eros: ritual dialogue and egalitarianism in three Central African hunter-gatherer societies. J. R. Anthropol. Inst. 19, 697–715.
Fritz, C., 1999. Towards the reconstruction of magdalenian artistic techniques: the contribution of microscopic analysis of mobiliary art. Camb. Archaeol. J. 9 (2), 189–208.
Fritz, C., Tosello, G., 2007. The hidden meaning of forms: methods of recording palaeolithic art. J. Archaeol. Method Theory 14 (1), 48–80.
Garate, D., Rivero, O., Ríos-Garaizar, J., Arriolabengoa, M., Medina-Alcaide, M.Á., Ruiz-López, J.F., Intzaurbe, I., Salazar, S., Libano, I., 2020. The Cave of Atxurra: A new major Magdalenian rock art sanctuary in Northern Spain. J. Archaeol. Sci. Reports 29, 102210. https://doi.org/10.1016/j.jasrep.2019.102120.
García, C.B., Castillejo, A.F.M., 2015. Interpretar la oscuridad: cuevas, art rupestre y análisis de luz simulada mediante escenas virtuales. Virtual Archaeol. Rev. 6 (12), 5–18.
García Moreno, A., Garate, D., 2015. Low-cost photogrammetry and 3D scanning: the documentation of palaeolithic parietal art in El Niño Cave. In: Chrysanthi, A., Wheatley, D., Romanawska, I., Papadopoulos, C., Murrieta-Flores, P., Sly, T., Earl, G., Verhagen, P. (Eds.), Archaeology in the Digital Era. Amsterdam University Press, Amsterdam, pp. 344–349.
García-Diez, M., Smith, P., Muñoz, E., Garrido, D., Ibero, Á., López-Calle, P., Ochoa, B., 2021. Visiting palaeolithic art – explorations and archaeological implications in Cueva De Las Monedas, Spain. Oxf. J. Archaeol. 40, 309–322.
González-Aguilera, D., Muñoz-Nieto, A., Gómez-Lahoz, J., Herrerop Pascual, J., Gutierrez-Alonso, G., 2009. 3D digital surveying and modelling of cave geometry: application to paleolithic rock art. Sensors 9, 1108–1127.
Gould, R.A., 1971. Uses and effects of fire among the western desert aborigines of Australia. Mankind 8, 14–24.
Grøn, O., Turov, M., Kokkerens, T., 2008. Settling in the landscape - settling the land: Ideological aspects of territoriality in a Siberian hunter-gatherer society. In: Olofsson, A. (Ed.), Archaeology of Settlements and Landscapes in the North. Vuollerim, Umeå, pp. 57–80.
Güth, A., 2012. Using 3D scanning in the investigation of Upper Palaeolithic engravings: first results of a pilot study. J. Archaeol. Sci. 39, 3105–3114.
Harman J., 2008. Using Decorrelation Stretch to Enhance Rock Art Images. Recovered 5th May, 2021. <http://www.dstretch.com/AlgorithmDescription.html>.
Hoare, S., 2020. Assessing the function of palaeolithic hearths: experiments on intensity of luminosity and radiative heat outputs from differential fuel sources. J. Paleol. Archaeol. 3, 531–559.
Hodgson, D., 2003. Seeing the 'unseen': fragmented cues and the implicit in palaeolithic art. Camb. Archaeol. J. 13 (1), 97–106.
Hodgson, D., 2006. Altered states of consciousness and palaeoart: an alternative neurovisual explanation. Camb. Archaeol. J. 16 (1), 27–37.
Hodgson, D., 2008. The visual dynamics of upper palaeolithic cave art. Camb. Archaeol. J. 18 (3), 341–353.
Hodgson, D., 2012. Emanations of the mind: upper paleolithic art as a visual phenomenon. Time and Mind 5 (2), 185–193.
Hodgson, D., 2021. Upper Palaeolithic art as a perceptual search for magical images. Time and Mind 14 (4), 487–499.
Hodgson, D., Pettitt, P., 2018. The origins of iconic depictions: a falsifiable model derived from the visual science of palaeolithic cave art and world rock art. Camb. Archaeol. J. 28 (4), 591–612.
Hoffmeister, D., 2017. Simulation of tallow lamp light within the 3D model of the Ardales Cave, Spain. Quat. Int. 430, 22–29.
Imura, T., Yamaguchi, M.K., Kanazawa, S., Shirai, N., Otsuka, Y., Tomonaga, M., Yagi, A., 2006. Perception of motion trajectory of object from the moving cast shadow in infants. Vision Res. 46 (5), 652–657.
Imura, T., Shirai, N., Tomonaga, M., Yamaguchi, M.K., Yagi, A., 2008. Asymmetry in the perception of motion in depth induced by moving cast shadows. J. Vis. 8 (13), 1–8.
Intxaurbe, I., Rivero, O., Medina-Alcaide, M.Á., Arriolabengoa, M., Ríos-Garaizar, J., Salazar, S., Ruiz-López, J.F., Ortega-Martínez, P., Garate, D., 2020. Hidden images in Atxurra Cave (Northern Spain): a new proposal for visibility analyses of Palaeolithic rock art in subterranean environments. Quat. Int. 566–567, 163–170.
Jouteau, A., Feruglio, V., Bourdier, C., Camus, H., Ferrier, C., Santos, F., Jaubert, J., 2019. Choosing rock art locations: Geological parameters and social behaviours. The example of Cussac Cave (Dordogne, France). J. Archaeol. Sci. 105, 81–96.
Jouteau, A., Fergulio, V., Lacanette, D., Carre, S., Noe, N., Jaubert, J., 2020. Understanding the perception and appropriation of space in Palaeolithic decorated caves: new methods and tools, with the examples of Cussac and Lascaux caves. Rock Art Res.: J. Austr. Rock Art Res. Assoc. (AURA) 37 (2), 137–154.
Kabukcu, C., Hunt, C., Hill, E., Pomeroy, E., Reynolds, T., Barker, G., Asouti, E., 2022. Cooking in caves: Palaeolithic carbonised plant food remains from Franchthi and Shanidar. Antiquity 97 (391), 12–28.
Katsuyama, N., Usui, N., Nose, I., Taira, M., 2011. Perception of object motion in three-dimensional space induced by cast shadows. Neuroimage 54 (1), 485–494.
Kedar, Y., Kedar, G., Barkai, R., 2020. Setting fire in a Paleolithic Cave: The influence of cave dimensions on smoke dispersal. J. Archaeol. Sci. Reports 29, 102112. https://doi.org/10.1016/j.jasrep.2019.102112.
Kedar, Y., Kedar, G., Barkai, R., 2021. Hypoxia in Paleolithic decorated caves: the use of artificial light in deep caves reduces oxygen concentration and induces altered states of consciousness. Time and Mind: J. Archaeol. Conscious. Culture 14 (2), 181–216.
Kersten, D., Knill, D.C., Mamassian, P., Bülthoff, I., 1996. Illusory motion from shadows. Nature 379, 31.
Kombeiz, O., Steidle, A., 2018. Facilitation of creative performance by using blue and red accent lighting in work and learning areas. Ergonomics 61 (3), 456–463. https://doi.org/10.1080/00140139.2017.1349940.
Kombeiz, O., Steidle, A., Dietl, E., 2017. View it in a different light: Mediated and moderated effects of dim warm light on collaborative conflict resolution. J. Environ. Psychol. 51, 270–283.
Le Quellec, J.-L., Duquesnoy, F., Defrasne, C., 2015. Digital image enhancement with DStretch®: Is complexity always necessary for efficiency? Digital Appl. Archaeol. Cult. Heritage 2 (2–3), 55–67.
Lerma, J.L., Navarro, S., Cabrellas, M., Villaverde, V., 2010. Terrestrial laser scanning and close range photogrammetry for 3D archaeological documentation: the Upper Palaeolithic Cave of Papalló as a case study. J. Archaeol. Sci. 37, 499–507.
Lewis-Williams, J.D., 1997. Agency, art and altered consciousness: a motif in French (Quercy) upper palaeolithic parietal art. Antiquity 71, 810–830.
Lewis-Williams, J.D., 2004. Neuropsychology and upper palaeolithic art: observations on the progress of altered states of consciousness. Camb. Archaeol. J. 14 (1), 107–111.
Lewis-Williams, J.D., Clottes, J., 1998. The mind in the cave – the cave in the mind: altered consciousness in the upper palaeolithic. Anthropol. Conscious. 9 (1), 13–21.
Lewis-Williams, J.D., Dowson, T., 1988. The signs of all times: entoptic phenomena in upper palaeolithic art. Curr. Anthropol. 29 (2), 201–217.
Lewis-Williams, J.D., Dowson, T.A., 1990. Through the veil: san rock paintings and the rock face. South African Archaeol. Bull. 45 (151), 5–16.
Mallol, C., Henry, A., 2017. Ethnoarchaeology of paleolithic fire. Curr. Anthropol. 58, S217–S229.
Mamassian, P., Knill, D.C., Kersten, D., 1998. The perception of cast shadows. Trends Cogn. Sci. 2 (8), 288–295.
Man-Estier, E., Deneuve, E., Paillet, P., Loiseau, L., Cretin, C., 2015. Something new in Combarelles I (Les Eyzies-de-Tayac, Dordogne, France). Paleo 26, 201–214.
Marquer, L., Otto, T., Nespoulet, R., Chiotti, L., 2010. A new approach to study fuel used in hearths by hunter-gatherers at the Upper Palaeolithic site of Abri Pataud (Dordogne, France). J. Archaeol. Sci. 37, 2735–2746.
Marshack, A., 1972. Cognitive aspects of upper paleolithic engraving. Curr. Anthropol. 14 (3), 445–477.
Marshall, L., 1961. Sharing, talking, and giving: relief of social tensions among !Kung Bushmen. Africa: J. Int. African Inst. 31 (3), 231–249.
Marshall, L., 1969. The medicine dance of the !Kung Bushmen. Africa: J. Int. African Inst. 39 (4), 347–381.

Mazel, A., 2021. Dancing in the dark with firelight: the power of shaded paintings in the uKhahlamba-Drakensberg and surrounding areas, southeastern Africa. In: Charette, C., Mazel, A., Nash, G. (Eds.), Indigenous Heritage and Rock Art: Worldwide Research in Memory of Daniel Arsenault. Archaeopress, Oxford, pp. 1–13.
McCauley, B., Collard, M., Sandgathe, D.A., 2020. Cross-cultural survey of on-site fire use by recent hunter-gatherers: implications for research on palaeolithic pyrotechnology. J. Paleoli. Archaeol. 3, 560–578.
Medina-Alcaide, M.A., Sanchidrián Torti, J.L., Peña, L.Z., 2015. Lighting the dark: Wood charcoal analysis from Cueva de Nerja (Málaga, Spain) as a tool to explore the context of Palaeolithic rock art. C. R. Palevol 14 (5), 411–422.
Medina-Alcaide, M.A., Cabalín, L.M., Laserna, J., Sanchidrián, J.L., Torres, A.J., Inxtaurbe, I., Cosano, S., Romero, A., 2019. Multianalytical and multiproxy approach to the characterization of a Paleolithic lamp. An example in Nerja cave (Southern Iberian Peninsula). J. Archaeol. Sci.Reports 28, 1–8. https://doi.org/10.1016/j.jasrep.2019.102021.
Medina-Alcaide, M.A., Garate, D., Intxaurbe, I., Sanchidrián, J.L., Rivero, O., Ferrier, C., Mesa, M.D., Pereña, J., Libano, I., 2021. The conquest of the dark spaces: an experimental approach to lighting systems in Paleolithic caves. PLoS One 16 (6), e0250497.
Meyering, L.-E., Kentridge, R., Pettitt, P., 2020. The visual psychology of European Upper Palaeolithic figurative art: using Bubbles to understand outline depictions. World Archaeol. 52 (2), 205–222.
Moník, M., Nerudová, Z., Schnabl, P., 2017. Experimental Heating of Moravian Cherts and its Implications for Palaeolithic Chipped Stone Assemblages. Archaeometry 59 (6), 1190–1206.
Moure Romanillo, A., González Sainz, C., Bernaldo de Quirós, F., Cabrera, V., 1996. Dataciones absolutas de pigmentos en cuevas cantábricas: Altamira, El Castillo, Chimeneas y Las Monedas. In: Moure Romanillo, A. (Ed.), "El Hombre Fósil" 80 años después. Universidad de Cantabria, Santander, pp. 295–324.
Mudge, M., Malzbender, T., Schroer, C., Lum, M., 2006. New reflection transformation imaging methods for rock art and multiple-viewpoint display. In: Ioannides, M., Arnold, D., Niccolucci, F., Mania, K. (Eds.), The 7th International Symposium on Virtual Reality, Archaeology and Cultural Heritage. The Eurographics Association, Switzerland, pp. 195–202.
Murphree, W.C., Aldeias, V., 2022. The evolution of pyrotechnology in the Upper Palaeolithic of Europe. Archaeol. Anthropol. Sci. 14 (202) https://doi.org/10.1007/s12520-022-01660-w.
Nakazawa, Y., Straus, L.G., González-Morales, M.R., Cuenca Solana, D., Saiz, J.C., 2009. On stone-boiling technology in the Upper Paleolithic: behavioral implications from an Early Magalenian hearth in El Mirón Cave, Cantabria, Spain. J. Archaeol. Sci. 36, 684–693.
Needham, A., 2017. Palaeolithic Art: More than Meets the Eye? An Object Biography Approach to Engraved Stone Plaquettes from the Magdalenian Site of Montastruc, South-Central France. PhD Thesis. University of York.
Needham, A., Wisher, I., Langley, A., Amy, M., Little, A., 2022. Art by Firelight? Using experimental and digital techniques to explore Magdalenian engraved plaquette use at Montastruc (France). PLoS One 17 (4), e0266146.
Nyland, A.J., Stebergløkken, H., 2020. Changing perceptions of rock art: storying prehistoric worlds. World Archaeol. 52 (3), 503–520.
Ochoa, B., 2017. Espacio gráfico, visibilidad y tránsito cavernario: El uso de las cavidades con arte paleolítico en la Región Cantábrica. (Graphic Space, Visibility and Cave Transit: The use of caves with Palaeolithic art in the Cantabrian region). BAR International Series 2875. Oxford: BAR Publishing.
Page, A.E., Minter, T., Viguier, S., Bamberg Miliano, A., 2018. Hunter-gatherer health and development policy: how the promotion of sedentism worsens the Agta's health outcomes. Soc. Sci. Med. 197, 39–48.
Pastoors, A., Weniger, G.-C., 2011. Cave art in context: methods for the analysis of the spatial organization of cave sites. J. Archaeol. Res. 19 (4), 377–400.
Perlès, C., Vanhaeren, M., 2010. Black Cyclope neritea Marine Shell Ornaments in the Upper Palaeolithic and Mesolithic of Franchthi Cave, Greece: Arguments for Intentional Heat Treatment. J. Field Archaeol. 35 (3), 298–309.
Pettitt, P., 2016. Darkness visible. Shadows, art and the ritual experience of caves in Upper Palaeolithic Europe. In: Dowd, M., Hensey, R. (Eds.), The Archaeology of Darkness. Oxbow Books, Oxford, pp. 11–24.
Pettitt, P., Maximiano Castillejo, A., Arias, P., Ontañón Peredo, R., Harrison, R., 2014. New views on old hands: the context of stencils in El Castillo and La Garma caves (Cantabria, Spain). Antiquity 88 (339), 47–63.
Pettitt, P., Leluschko, S., Sakamoto, T., 2017. Light, human evolution, and the palaeolithic. In: Papadopoulos, C., Moyes, H. (Eds.), The Oxford Handbook of Light in Archaeology. Oxford University Press. https://doi.org/10.1093/oxfordhb/9780198788218.013.1.
Plisson, H., Zotkina, L.V., 2015. From 2D to 3D at macro- and microscopic scale in rock art studies. Dig. Appl. Archaeol. Cult. Heritage 2, 102–119.
Proulx, M.J., 2014. The perception of shape from shading in a new light. PeerJ 2, e363.
Quesada, E., Harman, J., 2019. A step further in rock art digital enhancements. DStretch on Gigapixel imaging. Dig. Appl. Archaeol. Cult. Heritage 13, e00098.
Reznikoff, I., 2014. The Ħal Saflieni Hypogeum: a link between Palaoelithic painted caves and Romanesque chapels? In: Eneix, L. (Ed.), Archaeoacoustics: the archaeology of sound. The OTS Foundation, Myakka City, pp. 45–50.
Ripoll Perello, E., 1980. The Cave of Las Monedas in Puente Viesgo (Santander). Monographs on Cave Art: Palaeolithic Art, No. 1. Barcelona: Diputación Provincial de Barcelona Insituto de Prehistoria y Arqueología.
Rivero, O., Garate, D., 2020. Motion and gesture: analysing artistic skills in palaeolithic art. J. Archaeol. Method Theory 27, 561–584.
Rivero, O., 2012. Una nueva mirada al arte mobiliar del Magdaleniense Medio de la Región Cantábrica y los Pirineos: la contribución del análisis de cadenas operativas. In: L'art pléistocène dans le monde, actes du Congrès IFRAO (Tarascon-sur-Ariège, 2010), symposium «Art mobilier pléistocène», Tarascon-sur-Ariège, Société préhistorique Ariège-Pyrénées (no spécial de Préhistoire, Art et Sociétés, 55–56: 1411–1426.
Robert, E., 2016. The role of the cave in the expression of prehistoric societies. Quat. Int. 432 (B), 59–65.
Sakamoto, T., Pettitt, P., Ontañon-Peredo, R., 2020. Upper palaeolithic installation art: topography, distortion, animation and participation in the production and experience of cantabrian cave art. Camb. Archaeol. J. 30 (4), 665–688.
Salmon, F., Ferrier, C., Lacanette, D., Mindeguia, J.-C., Leblanc, J.-C., Fritz, C., Sirieix, C., 2021. Numerical Reconstruction of Paleolithic Fires in the Chauvet-Pont d'Arc Cave (Ardèche, France). J. Archaeol. Method Theory 28, 604–616.
Scherjon, F., Bakels, C., MacDonald, K., Roebroeks, W., 2015. Burning the land: an ethnographic study of off-site fire use by current and historically documented foragers and implications for the interpretation of past fire practices in the landscape. Curr. Anthropol. 56 (3), 299–326.
Snowden, R., Thompson, P., Toscianko, T., 2006. Basic Vision: An Introduction to Visual Perception. Oxford University Press, Oxford.
Steidle, A., Werth, L., 2013. Freedom from constraints: darkness and dim illumination promote creativity. J. Environ. Psychol. 35, 67–80.
Steidle, A., Werth, L., Hanke, E.-V., 2011. You can't see much in the dark: darkness affects construal level and psychological distance. Soc. Psychol. 42 (3), 174–184.
Steidle, A., Hanke, E.-V., Werth, L., 2013. In the dark we cooperate: the situated nature of procedural embodiment. Soc. Cogn. 31 (2), 275–300.
Sugiyama, M.S., Reilly, K.J., 2023. Cross-cultural forager myth transmission rules: Implications for the emergence of cumulative culture. Evol. Hum. Behav. https://doi.org/10.1016/j.evolhumbehav.2023.01.012.
Théry-Parisot, I., Costamagno, S., Brugal, J.P., Guilbert, R., 2005. The use of bone as fuel during the Palaeolithic, experimental study of bone combustible properties. In: Mulville, J., Outram, A. (Eds.), The Archaeology of Milk and Fats, 9th ICAZ Conferences, Durham, 2002. Oxbow Books, Oxford, pp. 50–59.
Till, R., 2014. Sound archaeology: terminology, Palaeolithic cave art and the soundscape. World Archaeol. 46 (3), 292–304.
Tosello, G., 2003. Pierres Gravées de Périgord Magdalénien: Art, Symboles. Territoires, CNRS Editions.
Tosello, G., 2005. ¿Un contexto social para el arte mueble paleolítico en Francia? In: P. Arias Cabal, R. Ontañon-Peredo (Eds.) La materia del lenguaje prehistórico: El arte mueble paleolítico de Cantabria en su contexto. 2a edición corregida y aumentada. pg. 53–65. Madrid: Museo Arqueológico Nacional.
Vandiver, P.B., Soffer, O., Klima, B., Svoboda, J., 1989. The origins of ceramic technology at Dolni Věstonice, Czechoslovakia. Science 246 (4933), 1002–1008.
Waller, S.J., 2019. Hear here: prehistoric artists preferentially selected reverberant spaces and choice of subject matter underscores ritualistic use of sound. In: L. Büster, E. Warmenbol, D. Mlekuž (Eds.) Between Worlds: Understanding Ritual Cave Use in Later Prehistory. Springer, pp. 251–264. https://doi.org/10.1007/978-3-319-99022-4.
Wiessner, P., 2014. Embers of society: Firelight talk among the Ju/'hoasni Bushmen. Proc. Natl. Acad. Sci. 111 (39), 14027–14035.
Wisher, I., 2022. The Origins of Visual Culture? Psychological Foundations of Upper Palaeolithic Figurative Cart Art in Northern Spain. Durham University. PhD Thesis.
Wisher, I., Pettitt, P. and Kentridge, R. (forthcoming) Conversations with Caves: The Role of Pareidolia in the Upper Palaeolithic Figurative Art of Las Monedas and La Pasiega (Cantabria, Spain). Cambridge Archaeological Journal.
Zmigrod, S., Zmigrod, L., Hommel, B., 2015. Zooming into creativity: individual differences in attentional global-local biases are linked to creative thinking. Front. Psychol. 6 (1647), 1–8.