KEYWORDS: *Cussac – Lascaux – Parietal arrangement – Lighting simulations – Sound simulations*

UNDERSTANDING THE PERCEPTION AND APPROPRIATION OF SPACE IN PALAEOLITHIC DECORATED CAVES: NEW METHODS AND TOOLS, WITH THE EXAMPLES OF CUSSAC AND LASCAUX CAVES

Armance Jouteau, Valérie Feruglio, Delphine Lacanette, Samuel Carré, Nicolas Noé and Jacques Jaubert

Abstract. In order to better understand the purpose of parietal art for Palaeolithic groups, its role in society and the different uses it could have, we need to understand which factors impacted the construction of the parietal arrangement, the choice of decorated surfaces and their layout. The first part of this study investigates the nature of the rock support, location, surroundings, accessibility and visibility of 31 panels in the decorated cave of Cussac (Dordogne, France), where a multidisciplinary research program has been developed since 2008. For this purpose, a multidisciplinary criteria database was built to record such data. Then an innovative methodology was implemented combining a statistical study of the database (Factor Analysis for Mixed Data – FAMD) with the study of topographic documents completed on site. Three groups of panels have been brought to light, revealing three ways of using the cave. The first group is characterised by small panels located in narrow passageways, often on layered and irregular limestone, in the cave's Downstream Branch. They all offer strong potential for visual relationships, although they do not seem to be dedicated to a group of people. The second group also seems to have been dedicated to a restrictive group, but they are visually isolated from each other, they share fewer geologic and topographic criteria, and they are present in both the Upstream and the Downstream Branches. Finally, Group 3 panels are large panels, most of which have numerous motifs engraved on massive and regular limestone. They often share visual relationships with other panels, and they are all located in wide corridors of the Downstream Branch. Their size and location are consistent with the presence and participation of a small group of individuals.

This study yielded interesting results, but above all has highlighted a significant limitation: our modern lighting tools bias our space perception and influence our results and interpretations. In reaction to these biases, the second part of the study, which has just begun, aims to complete the first one using a three-dimensional survey of caves to simulate lighting and sounds as closely as possible to the ones the Palaeolithic people may have known. Two caves were chosen as they are complementary in their geomorphology and field access and the size of their three-dimensional surveys: Cussac and Lascaux caves (Dordogne, France). The primary purpose of this part of the study is to understand how lighting and acoustics influenced the construction of the parietal arrangement. However, before the study can be functional, an important phase calibrating the properties of the materials, sound sources and light sources must be done. As it is an exploratory study, one of our goals is also to determine the current technical and technological possibilities at our disposal.

I. Introduction

1. Project origins

The study of decorated caves is an idea that stemmed from structuralism (Raphaël 1945, 1986; Laming-Emperaire 1962; Leroi-Gourhan 1965), modified and renewed as discoveries have been made and new research conducted with new questions about the relationship between motifs and their environment, the place of potential viewers, or the acoustic qualities of the sites.

The primary purpose of our study is to develop reliable methods to study the internal spatial context of decorated caves, using modern scientific tools and excluding any interpretation based on perception and feelings.

First, we developed a method based on a statistical analysis of a database to understand the organisation of the parietal arrangement inside Cussac cave (Dordogne, France). The database recorded the distribution of the panels according to geological and geomorphological factors, the panels' fields of visibility, pathways and others (Jouteau 2016). This study, while giving us promising results, highlighted a significant bias: we could not perceive the subterranean space as the Palaeolithic groups did, and this has an impact on our results and their interpretation (Jouteau et al. 2019).

Therefore, in a second step, we seek to simulate visual and sound perception as close as possible to that of the Palaeolithic, in a three-dimensional survey of decorated caves. This second part of the study is still at an early stage and has two objectives, namely, to determine:

- The technical and technological possibilities at our disposal, according to our knowledge of the Palaeolithic, our computer tools, our understanding of the phenomena involved, and our access to the cavities under study.
- The influence of lighting and acoustics in the construction of the parietal arrangement.

We chose to apply the first method to Cussac cave because of its in-site accessibility, the presence of an interdisciplinary research team (geology, topography, dating, rock art, traces of activity) able to cross natural and cultural factors, the presence of a single culture (Middle Gravettian; Aujoulat et al. 2001, 2002; Jaubert et al. 2017), the cave's organisation of motifs in clearly defined panels along a single gallery, and the good state of preservation of the cave's panels, grounds, and general morphology since the Gravettian. However, the three-dimensional survey of the cave is incomplete, so to test the second method we decided to complete our study of Cussac cave with that of another cave that had benefited from a full three-dimensional survey.

The last complete three-dimensional survey of Lascaux cave was carried out in 2012 by Perazio Engineering, using laser scanning. We decided to add this particular cave to our study because it is complementary to Cussac cave in many respects: entry into the site is impossible in Lascaux but possible in Cussac (Fourment et al. 2012; Jaubert et al. 2012), while the three-dimensional survey is complete for Lascaux cave and only partial for Cussac cave. There are figurative paintings and fine engravings in Lascaux, due to the nature of the rock support (paintings are mainly found on calcitic support while engravings were done on soft limestone; Aujoulat 2005), while there are almost exclusively deep monumental engravings in Cussac (Aujoulat et al. 2001). Cussac cave consists of a single, very long corridor (1.6 km) while Lascaux cave is rather small and contains several chambers and corridors, intersections and shafts. Finally, in Cussac cave the motifs are organised in clearly disjointed panels, while there is an almost graphic continuity in Lascaux cave.

The work presented here is an ongoing study, focused on the development of a rigorous methodology for the application of new digital tools to the question of how Palaeolithic people understood the karstic world in their decoration of caves.

2. Integration of the project in a historical context

For many years, the study of Palaeolithic rock art was disconnected from its context, due to the influence of Henri Breuil who used to record figures out of their physical context (e.g. Cartailhac and Breuil 1906; Breuil and Bégouën 1958). At that time, rock art was considered to be the result of either pre-Historic people's hobbies (John Lubbock, Salomon Reinach, Gabriel de Mortillet; see Groenen 1994) or of magical rituals intended to bring fertility and ensure prolific hunting (Bégouën 1939; Breuil 1952). In this context, it is natural to think that the subterranean context itself had a low impact on the shape of motifs, the choices of figurative themes or graphical designs and the choice of their location.

These theories about rock art study were challenged during the 1960s following the death of the 'Pope of Prehistory', Henri Breuil, and a new trend was born: structuralism. It rests on the claim that decorated caves were sacred and organised places. Following the pioneering works of Max Raphaël and Annette Laming-Emperaire (Raphaël 1945, 1986; Laming-Emperaire 1962), the leader of this movement, André Leroi-Gourhan, even proposed a 'standard model' for the organisation of Palaeolithic decorated caves, which simplifies the cave's layout to the extreme (Leroi-Gourhan 1965). The link between the motif and its support was not studied. The choice of the location of the rock art was limited to studying the link between the theme and predefined places in the cavity. However, this movement led to a renewal of methods and tools, with the introduction of inventories and statistics. It also revealed that decorated caves are indeed structured spaces, which are now considered as a whole.

Following structuralism, a paradigm shift took place in archaeological research. Prehistorians no longer sought to interpret rock art or propose global models, but, influenced by the 'New Archaeology', they went on to focus on its cultural role and social value (Lorblanchet 1995, 1999; Clottes 1998). This led to the emergence of new questions about the artist's place, and role in his/her society (Fritz 1999; Feruglio et al. 2011), about the modalities of parietal arrangement (Lorblanchet 2010), and about the underlying purpose of creation: was the objective to show the work, or to mark the wall, the cavity or the site?

This quest for the social function of cave art and the natural context in which it is embedded can be subdivided into three research axes. These have been accompanied by the development of new technologies: the relationship between motifs and their support, relative to the wall (Lorblanchet 1993; Aujoulat et al. 2001; Ferrier et al. 2017) or the cave architecture (Vialou 1986; González García 2002); the perception of the subterranean space, with the study of lighting (Delluc and Delluc 1979; de Beaune 1983, 1987), acoustics (Reznikoff and Dauvois 1988; Reznikoff 2012; Fazenda et al. 2017), palaeospeleology (Rouzaud 1997) and internal context (Pastoors and Weniger 2011; Garate-Maidagan et al.

2015; Ledoux et al. 2017; Medina Alcaide et al. 2018); and the study of the recipient(s) of the graphic production (Villeneuve 2008; Bourdier et al. 2017).

These issues have been investigated thanks to the development of new tools, bringing with them new methods of analysis. In recent years, the development of computer science and the rise in the number of three-dimensional surveys of caves or portions of decorated caves have made a significant contribution to research in prehistory (Pinçon and Geneste 2010). These tools are used to study the cave and its natural context without entering the cave itself in order to avoid damaging it, as well as to carry out numerical simulations. Various software solutions propose realistic renderings of complex physical phenomena and have been used to simulate Palaeolithic lighting. This is the case, for example, of the Radiance software (Devlin et al. 2002) which was used to simulate grease lamp lighting at the Cap Blanc rockshelter. This simulation supports the hypothesis (without proving it) that Palaeolithic lighting could have animated the sculptures in the decorated shelter. Another example of light simulation was conducted in the Ardales cave (Hoffmeister et al. 2016; Hoffmeister 2017), where daylight simulation was used to determine to what extent the sunlight lit the cave. To simulate artificial lighting, the researchers used the Blender software, where light points were calibrated to take on characteristics like those of modern candles, considered similar to Palaeolithic grease lamps (de Beaune 1987), with a colour temperature of 1500 K, an intensity of 12 W, and a light source size of 40 mm. Their results confirm the investigations of Pastoors and Weniger (2011): this lighting is adequate for orientation in complete darkness, but several of these light sources are required to be able to observe the figures, especially when colour plays a vital role in their perception.

However, as these are realistic, but not real, renderings, it is impossible to go further in terms of interpretation. As the authors point out (Hoffmeister 2017), it would be necessary to incorporate information concerning the reflective behaviour of the materials present in the cave (limestone, clays, concretions and others) and to consider the adaptation of the eye to its environment and the brightness of screens.

Our study comes as part of the current ambition to better understand how pre-Historic people perceived and occupied the karstic environment, what connections they were able to establish between the natural environment and the motifs they placed on the walls, ceilings and floors of cavities, and why they assigned specific motifs to specific locations rather than others. To this end, we seek to investigate different modern analytical methods and tools to determine the advantages, disadvantages and biases brought by each one.

II. Site descriptions

To test our methods in various technical and archaeological conditions, we included two decorated caves in the study: Lascaux and Cussac. These two caves are complementary in various respects (Table 1).

1. Lascaux cave

The cave is located in Dordogne Department, on the left bank of the Vézère River (Fig. 1). The discoverers were four teenagers: Marcel Ravidat, Jacques Marsal, Georges Agniel and Simon Coencas. They entered the cave on 12th September 1940, and on 20th September H. Breuil visited the cave. During the first few months after the discovery, many people came to visit the cave. They included researchers but also many visitors from the surrounding villages. As no precautions were taken with the ground, it was trampled during this period. About the same time, the rimstone formations near the

	Lascaux	**Cussac**
Three-dimensional survey	Complete	Half of the Downstream Branch
Textured survey	Complete	Discovery Panel sector
Configuration	Galleries, chambers, shafts, intersections	Single gallery
In-site access	Impossible, but there is Lascaux IV, a facsimile	A few weeks every winter
Discovery	Old (1940)	Recent (2000)
Modifications	Major (Palaeolithic floors and entry significantly modified)	Minor (walkways on the ~50 cm wide pathway)
Parietal arrangement	Invasive/overwhelming/filling	Motifs grouped in panels
Techniques	Engraving, painting, drawing, mixed techniques	Domination of deep and monumental engravings
Culture	Solutrean/early Magdalenian?	Middle Gravettian
Archaeological remains	Numerous: flints, bones and reindeer antler tools, pigments, shell ornaments and grease lamps	Scarce flints and reindeer antler tools, grease lamps and human remains (NMI=6)

Table 1. *Summary description of Lascaux and Cussac caves.*

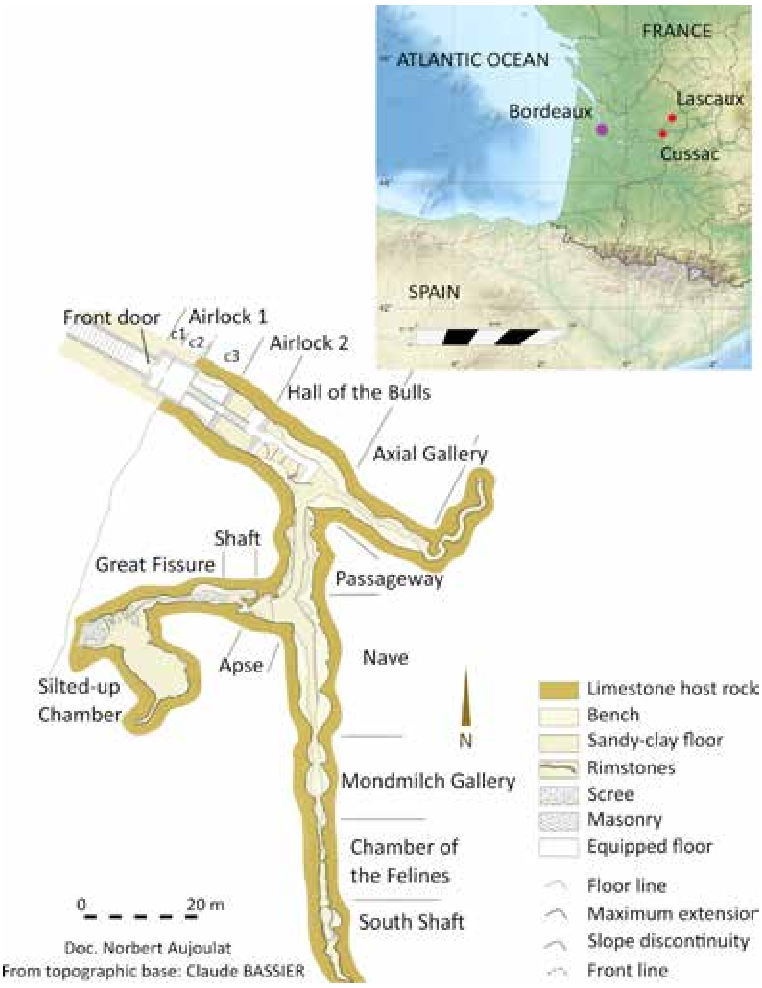

Figure 1. *Location and plan of Lascaux cave, modified from N. Aujoulat, on a topographic base by Claude Bassier of 1966 (Aujoulat 2004; CNP-MC).*

entrance were pierced. At the end of the 1940s, new modifications were made, especially in the entrance and the Hall of the Bulls, and Breuil and Blanc led an excavation in the Shaft (Aujoulat 2005).

The entrance scree was destroyed in 1947–48, during the work carried out to enable public access. The intense exploitation of the site for tourism led to a high CO_2 concentration and temperature, leading to visitor discomfort and condensation on the walls. In the late 1950s work was therefore done to install air ducts underground. These works included significant modifications to the ground and archaeological levels. However, at the beginning of the 1960s, green spots and calcite deposit were noticed on the walls and from that point on, access to the cave was increasingly restricted, first to visitors with the site's permanent closure in 1963, then to researchers (Aujoulat 2005; Lacanette and Malaurent 2010). This decision has only been validated by new issues such as the proliferation of microorganisms discovered in 2001 (Noël 2011; Mauriac and Rieu 2017; Saiz-Jimenez and Alabouvette 2017).

Today, no in-site studies are possible, but in 2012, a three-dimensional survey of the entire cavity was performed. This survey recorded the modern morphology of the cave, thus with its destroyed grounds. Serving as a relay for the scientific study, it was initially used to help in the preservation of the site and to offer a better understanding of its microclimatic behaviour (e.g. Lacanette and Malaurent 2014). It was then used for the creation of a new facsimile, Lascaux IV, and is now being used in the field of archaeological research, with programs to reproduce the state of the ground at the moment of discovery (September 1940) and in Palaeolithic times (project MicroPaGO, dir. D. Lacanette, IdEx funding, then Ministry of Culture), and to connect the archaeological remains to the Palaeolithic grounds (PCR LAsCO, dir. M. Langlais, funding Ministry of Culture).

The cavity is in Upper Coniacian limestone and follows the hydrographic network of the region. Consequently, the cave is made up of several galleries running in different directions (Fig. 1). The infiltrations occurred through a joint, resulting in a profile which is higher than wide in most galleries. These galleries have a keyhole profile and domed roofs, sometimes with several interlocking domes. The limestone is quite clear and soft enough to have been engraved in some places. Sometimes it is covered with a thin layer of white calcite, which makes the support unsuitable for engraving, but ensures that the colours stand out and are well preserved (Aujoulat 2002).

Lascaux cave is known for the number and incredible density of its motifs (almost 2000 motifs recorded; Aujoulat 2005), accomplished in a uniform style but using various techniques. Engraving is combined — sometimes on the same line — with drawing and painting in various colours (yellow, red, black, brown and even mauve). These decorations have been more or less well preserved depending on the different sectors of the cave, while the colours have sometimes kept the fresh glow that makes the site famous (Fig. 2a), or else they have faded or the calcite crust has collapsed, leaving only fragments (Fig. 2b). The themes correspond to the classical themes of Palaeolithic parietal art in south-west Europe, with some peculiarities: horses, aurochs and deer dominate the bestiary, to which are added bison, ibex, bear, rhinoceros, reindeer, imaginary or composite beings (like an anthropomorph with bird head), and an anthropomorphous figure, but without any mammoths. Although more discreet, there are numerous 'signs' in the cave, representing more than 22% of all motifs (Aujoulat 2005).

Lascaux is one of the decorated caves with the most abundant archaeological context, despite numerous ground destructions without prior excavation (more than 700 artefacts mentioned so far; Leroi-Gourhan and Allain 1979). Most of the artefacts were discovered progressively, from the first incursions into the cave to André Glory's excavations in the Shaft in the early 1960s. Some of the artefacts have since been lost. Various categories of objects have been found: flint tools, reindeer antlers and tools made of bones and antlers, pigments, shell ornaments and grease lamps (Leroi-Gourhan and Allain 1979).

As charcoal was not used as a pigment, it is impossible to date the paintings directly, and the chronological estimation of Lascaux cave art has long been a matter of debate. The style of the figures seems to be related to the end of the Solutrean (e.g. Aujoulat 2005), or at least ante-Middle Magdalenian, while the flint industry is related to the Early Magdalenian (Allain 1979). The dating of a reindeer antler and a fragment of a spear tip yielded an age between 23 500 and 22 000 cal BP (Aujoulat et al. 1998; Valladas et al. 2013), which corresponds to the end of the Solutrean, although these dates are contested. At present, the scientific community as a whole suggests an age between 24 000 and 18 000 cal BP, or even 22 000–20 000 cal BP (Delluc and Dulluc 2012), which would correspond to the very beginning of the Magdalenian. One of the objectives of the DEX_TER/LAsCO project (dir. S. Ducasse and M. Langlais) is to review the archaeological remains discovered in Lascaux and other chronologically similar sites in order to improve their chronology.

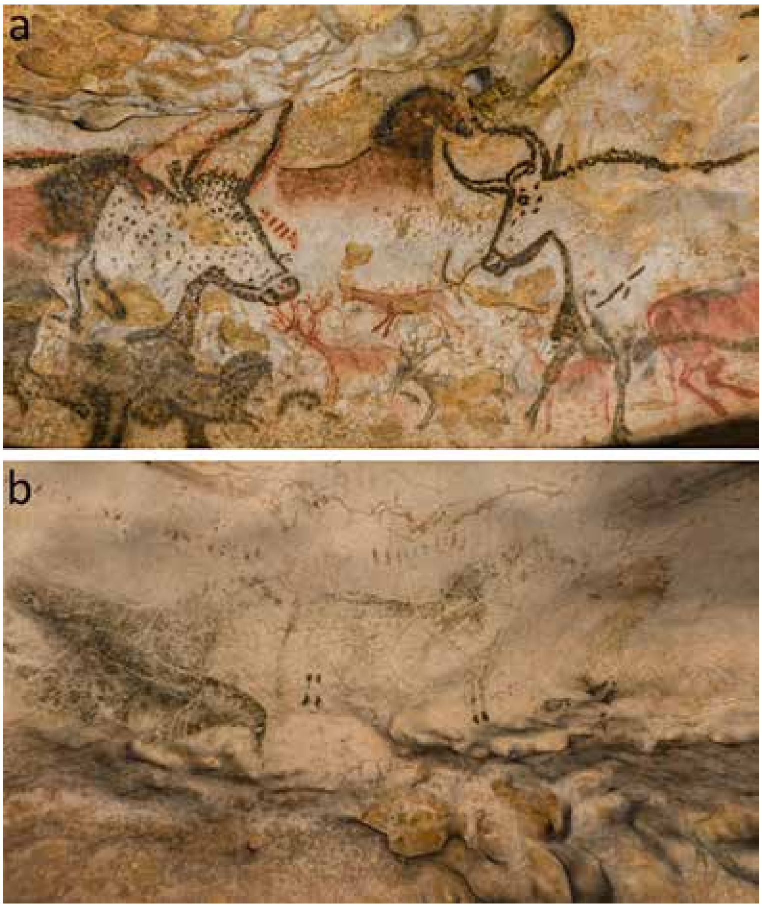

Figure 2. (a) Hall of the Bulls, well-preserved portion of the left wall with horses, aurochs and deer; (b) Chamber of the Felines, fading portion of the right wall with horses (pictures obtained from the three-dimensional survey carried out by Perazio Engineering, French Ministry of Culture).

2. Cussac cave

Cussac cave is a decorated cave, but also a sepulchral site (Henry-Gambier et al. 2013) located in Dordogne Department (France), on the right bank of the Bélingou, a tributary of the Dordogne River. It was discovered in 2000 by Marc Delluc after he passed by the entrance porch and a narrow aperture. He walked 130 metres into the cave and discovered a first engraved panel (Discovery Panel) and human remains. He had the foresight to walk only on a narrow path, contributing to the excellent state of preservation of the cave (Aujoulat et al. 2001). This path is the only authorised route inside the cave, restricting study conditions but ensuring ground preservation, and is now equipped with walkways. The Ministry of Culture now owns the site and has classified it as 'Cultural Heritage' (Fourment et al. 2012).

In 2008, under the direction of one of the authors of this paper, a scientific team was formed to conduct an interdisciplinary research project (PCR Cussac, dir. J. Jaubert, funding Ministry of Culture; Jaubert et al. 2012, Jaubert 2015), the main aims of which were to contextualise the site in its natural and cultural environment, to identify reasons why this site was chosen, and to understand its frequentation modalities. For this purpose, several shared recording and analysis tools were developed, including detailed topography, three-dimensional laser scanning, photogrammetry, GIS (ongoing development) and cloud storage of documents. As the site is only accessible a few months a year, and the cave is not entirely accessible for conservation purposes (only one pathway is followed), three-dimensional recordings are a help to researchers (Aujoulat et al. 2013; Feruglio et al. 2015).

As Cussac cave is a recent discovery, the site, the grounds and the general morphology are very well preserved. However, the study is ongoing, and not all the motifs have been recorded or even discovered.

The cave is a 1.6 km long single gallery, subdivided from the entrance into a Downstream Branch and an Upstream Branch (Fig. 3). All along the gallery, the ground is subhorizontal, mainly composed of clayey sediments which have preserved numerous human and animal prints, but also of collapsed blocks, some dating from after the Gravettian (mainly in the Upstream Branch).

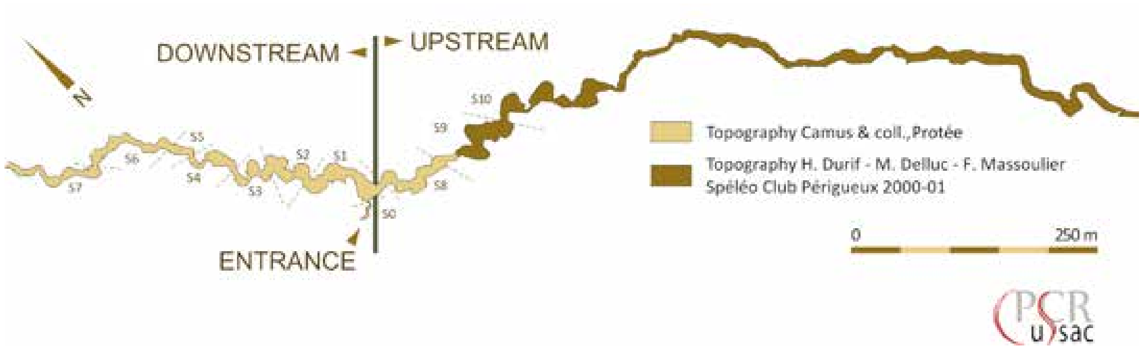

Figure 3. Location and plan of Cussac cave, produced by the Protée company (H. Camus and coll., 2010–2011) and H. Durif, M. Delluc and F. Massoulier, 2000–2001.

The cavity occurs in Campanian limestone and is subdivided into two facies (Ferrier et al. 2017). The upper part of the cavity is a massive, smooth, regular limestone, especially well adapted to engravings because it is soft and thus easily engraved (even with fingers). The engraving is white because it reveals the limestone behind the surface, while the surface is orange, having suffered from partial dissolution. Below, the limestone is composed of layers tens of centimetres thick. These beds are harder, the engravings are thus less remarkable, and numerous joints all over this facies make the engraving more challenging to read.

More than 800 motifs ('graphic units') have already been recognised so far in the cave, some of which are isolated figures while others are distributed among the main panels (up to 130 engravings on the Grand Panel: Feruglio et al. 2019). Their size ranges from a few centimetres to more than three and a half metres for the biggest bison in the cave (Fig. 4). Almost all the graphic elements are engraved, including through finger tracing (a few ochre and manganese spots and dots break up this uniformity). The figurative themes are typical of the Middle Gravettian, with bison, mammoths and horses as the dominant species, along with depictions of other bovines, deer, rhinoceros and geese, imaginary animals, female figures and sexual representations of females and males. These figurative themes and their associations and stylistic conventions in Cussac cave are characteristic of the Middle Gravettian and can be found in other caves such as Gargas (Hautes-Pyrénées) and Pech-Merle (Lot) (Aujoulat et al. 2004, 2013; Lorblanchet 2010; Jaubert 2008; Feruglio et al. 2011; Jaubert and Feruglio 2013; Petrognani 2013).

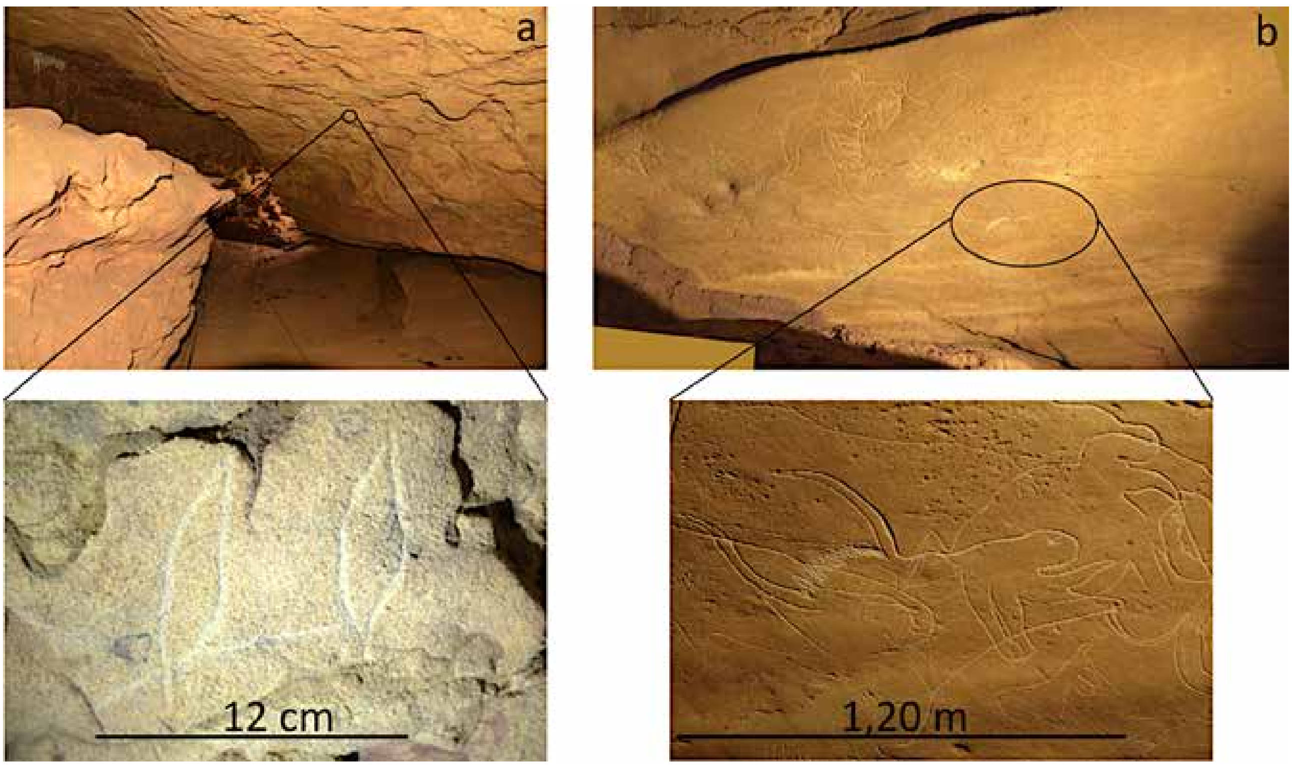

Figure 4. (a) Panel 3D1 'the fusiforms' (ph. V. Feruglio, A. Jouteau/MC), close-up of the motif: the fusiforms (ph. V. Feruglio/MC). (b) Reconstruction of panel 5G2, 'Grand Panel' (V. Feruglio) through an assembled mosaic of photos (ph. N. Aujoulat/MC), close-up of the head of the Great Bison (ph. V. Feruglio, C. Bourdier/MC).

Cussac Cave is one of France's major Palaeolithic decorated caves, not only because of its spectacular engraved art but also because it contains the human remains of at least six individuals, all deposited in or near bear hibernation pits (Henry-Gambier et al. 2013). Only one seems to have anatomical articulation. This individual, probably a young man, was deposited in the ventral position in a bear pit numbered Locus 2 / L2 (Villotte et al. 2015). The human remains deposited in Loci 1, and 3 are more numerous, mixed, and without any anatomical connections revealed so far. This may be due to a secondary deposit (rare in the Gravettian period) or to a more troubled taphonomic history. Ochre was found to be associated with Loci 1 and 3, confirming their intentional deposition (Henry-Gambier et al. 2013). Excavations are planned for Locus 1, in order to better understand the modalities of the deposit and to obtain biological information on the individuals.

Very few artefacts have been found so far, possibly because no excavation was intended since ground preservation was the priority. One laminar flake and two flint blades were found in the Downstream Branch (Klaric in Jaubert et al. 2012 and Ledoux et al. 2017), as well as one cervid antler rod (Goutas in Jaubert et al. 2012 and Ledoux et al. 2017) and two lamps in the Upstream Branch. Portions of broken and displaced speleothems, torch smears, ochre and manganese dots and footprints and other body prints are further hints of human frequentation of the cave (Ledoux et al. 2017).

As relative chronological elements (lithic and bone technology, parietal art, funerary practices) seem to converge towards the Middle Gravettian, one human bone and two charcoal fragments were dated to 29704–28714 cal BP and 31274–29521 cal BP for the latter, and 29500–28835 cal BP for the human bone (OxCal 4.2 © Christopher Bronk Ramsey 2014; IntCal 13, Reimer et al. 2013), confirming a Middle Gravettian age, around 28–29000 cal BP (Jaubert et al. 2017). The incursions of bears preceded those of humans.

III. Presentation of the in-situ method, example of Cussac cave

This method and the results have already been presented in detail (Jouteau et al. 2019), but it seems important to recall here the main points in order to understand the approach applied.

1. Issues

In Cussac cave, there seem to be two opposing types of panel: panels with many figures, which sometimes overlap to form palimpsests, and panels with few figures, including some with only one. Also, the overall distribution of panels within the cavity appears to be uneven, with areas more densely decorated than others, and no direct link could be established with the human remains. The distribution of the motifs grouped into very distinct panels several metres apart led the scientific team to wonder whether these panels had a particular distribution, and if so, which. To this end, some questions were raised:

- Do the geology and geomorphology of the cave influence the location of the panels? Does this location depend on the type of panels?
- Which potential audience were they aimed at (Image-makers only? Viewers? A spiritual entity?)?
- How are the panels distributed all along the cavity?
- Could these panels have played different roles in the Palaeolithic appropriation and use of the cavity?

The purpose of these questions is to understand which criteria influenced Gravettian people in creating the parietal arrangement and interpreting these criteria in terms of behaviour.

2. Methodology

Choice of sectors to be investigated

Because of the size of the cave (1600 m long) and the large number of panels (~70 according to the 2017 campaign), a selection of the panels to be studied was carried out. We prioritised the entrance, the beginning of the Upstream Branch, and the first two-thirds of the Downstream Branch because this sector contains the highest density of engravings, which are variously distributed, easily accessible and well documented in previous studies about the cave's rock art, geology and geomorphology. The panels that may also have been unintentional marks (such as diffuse red traces) were not recorded. In all, the study comprises 31 panels (27 from the Downstream Branch and four from the Upstream Branch). This is a first selection to test our method, but the other panels will be included when the cavity is entirely equipped for the study, and the method will be improved.

For this selection, we did not consider the availability of the 3D model, because the study was entirely done in the field, during a winter field campaign, when the CO_2 level is at its lowest.

Database development

In the field, several criteria were recorded in a database. We chose this first mode of data acquisition in order to use statistics to determine which factors are most frequently related to the presence of a panel and therefore seem to have been decisive in the choice of the position of the panels.

The 49 variables in the database are subdivided into five sets briefly described below (for more details, see Jouteau et al. 2019):

- 'Panel composition': including the number of motifs, the degree of overlap of the motifs, the organisation of the engravings within the panel.
- 'Appearance of the support': these are criteria related to the geology and morphology of the support and its alterations (animal or geological).
- 'Physical context of the support': this is the description of the environment of the support: floor, the shape of the gallery, presence of other panels, delimitations of the support and its location (height, inclination and distance to the natural path).

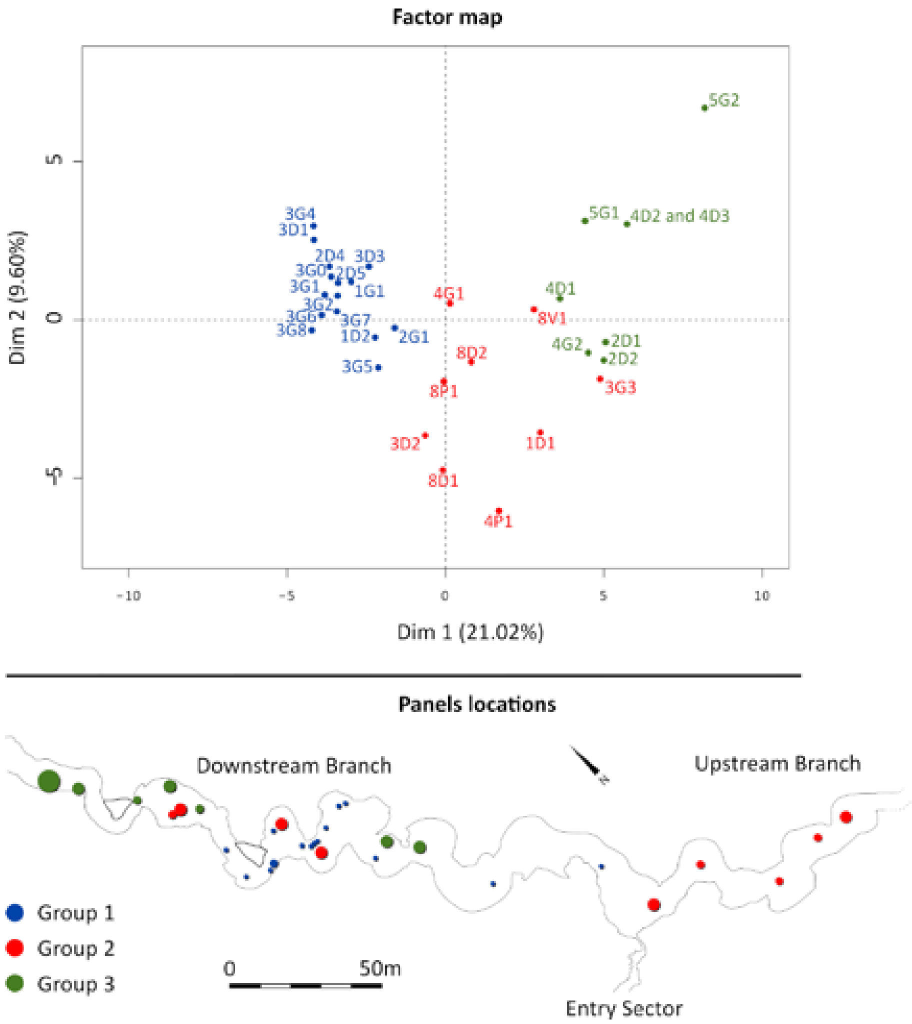

Figure 5. Factor map of the studied panels and their location inside the cave (from Jouteau et al. 2019).

- 'Accessibility of the support for the engraver': this describes the access to the panel, the conditions for working on it, and the need to move or not to create the panel.
- 'Accessibility and visibility of the panel surface for a potential audience': can the panel be observed without prior indication, from what distance is the panel visible, in which direction is it oriented, how many and what kind of lighting sources were needed to illuminate it? The access conditions and the ideal observation point (when determined) were also reported.

The database was then processed using the R software (R Core team 2018). We performed a Factorial Analysis for Mixed Data (FAMD) to compute the principal axis deriving directly from both numeric and nominal data. This is preferable because the database has a relatively small sample, with only five continuous variables and 44 categorical factors (Pages 2004).

To identify homogeneous clusters of panels, the factorial coordinates of the individuals were used to perform an agglomerative hierarchical clustering according to Ward's method. These multivariate analyses were conducted using the R package FactoMineR (Le et al. 2008). The missing values were imputed before applying FAMD, using a regularised iterative algorithm (Audigier et al. 2016) implemented in the R package missMDA (Josse and Jusson 2016).

Use of topographic maps

Camus and collaborators (Protée company) produced topographic maps of the studied areas in 2010 and 2011. In the field, they completed the database, indicating: the extent of the panel; the different accesses to the panels; the verified (precise laser telemeter measurements were taken) or potential (no measurements could be taken in the field because of the distance to the current pathway) visibility fields; the ideal observation area where possible (area from which the motifs can be observed while standing); and the major topographical obstacles, which may or may not be overcome.

Photographs and sections of the cavity were also used to complete these maps. The objective was to highlight the position of the panels, their environment, and access to them. This made it possible to reproduce the space around the panels, even where they are inaccessible.

3. Results

Statistical analysis

As presented in a previous study (Jouteau et al. 2019), after a hierarchical clustering on the FAMD coordinates, three groups of panels emerged (Fig. 5). This study details which modalities are linked with each axis and thus are associated with different groups of panels. Here we only present an overview of these groups.

The first group clustered all the small panels containing one or two motifs. These are always in narrow galleries, most often engraved on a layered limestone. They are also all located in the Downstream Branch, mainly in its centre (Fig. 5). Very few people can observe them simultaneously, and their maximum distance of visibility is the shortest (mean of 6.8 m).

The second group contains panels with between two and ten engravings, although the appearance of their support does not seem decisive, and their maximum distances of visibility are more varied. Still, they are often located above the Palaeolithic pathway, so it is necessary to walk under them to move forward inside the cave. They are also the only group present in the Upstream Branch sector, although they are also present in the Downstream Branch.

The third group comprises the biggest panels in the cavity, often with more than ten figures. Within a single panel, these engravings can overlap one another several times, to the extent of forming palimpsests. They are always engraved on ceilings of massive and regular limestone, and the engraver often limited the extent of the panel according to the height below the ceiling. Although access to them can be difficult, and outside of the natural pathway, they are situated in extensive galleries where a group of people can observe them at the same time, and their maximum distance of visibility is always above ten metres. They are only located in the Downstream Branch.

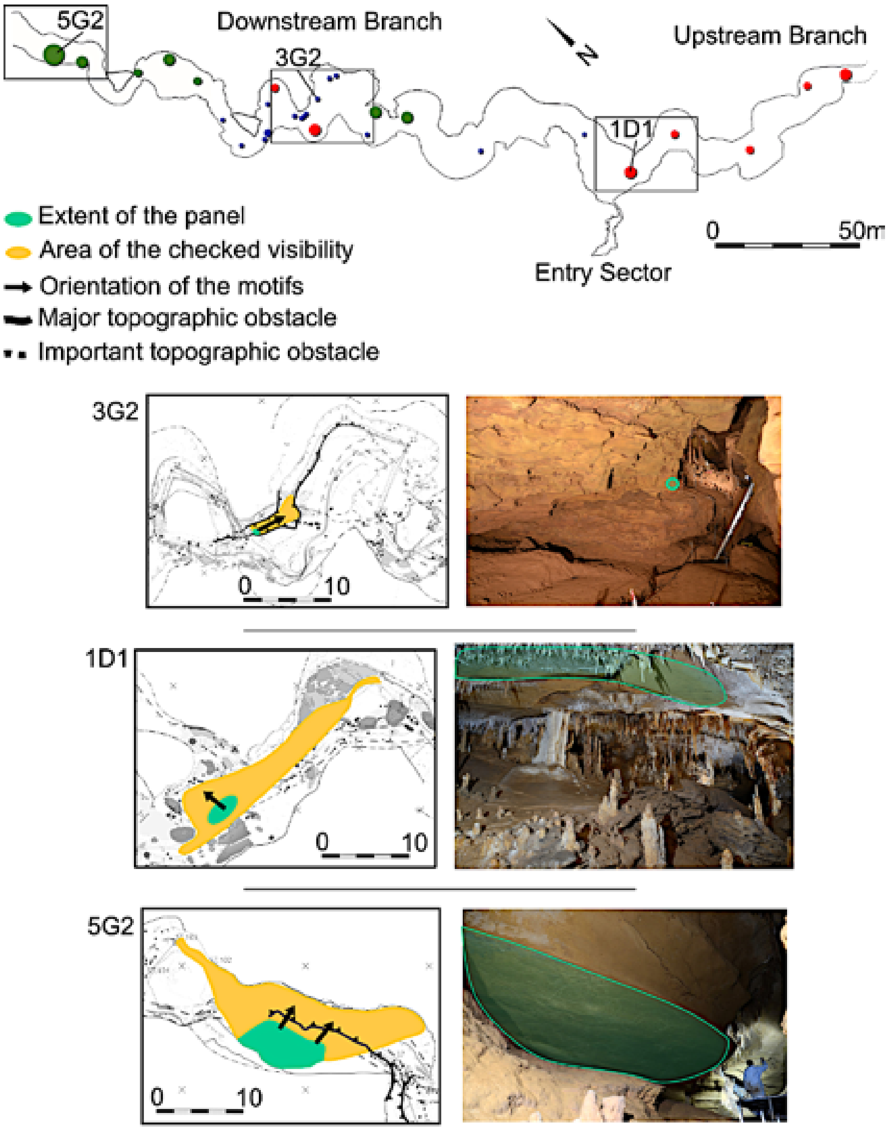

Figure 6. Examples of fields of visibility for each group (panel 2D5 for group 1, panel 1D1 for group 2 and 5G2 for group 3, from Jouteau et al. 2019).

Analysis of the visibility areas on topographic maps

The fields of visibility of the panels also differ between the three groups (Jouteau et al. 2019). Because they are in narrow galleries, the fields of visibility of group 1 panels are very elongated, and no more than three people can observe them at the same time (Fig. 6). Three of them are oriented towards the upstream area and are only visible in an upstream-to-downstream direction, one is only visible from downstream, and the eleven others can be seen regardless of the direction.

The fields of visibility of the second group are more varied than the first in size, although they are always quite large. The motifs are never oriented towards the furthest point of visibility (Fig. 6). Thus, it was possible to see the panels from afar with adapted lighting, but a big group of people could not observe the motifs at the same time.

Conversely, the fields of visibility of the panels in the third group are extensive, so it was easy for a group of people to observe them at the same time (Fig. 6). They are always oriented towards the path in an upstream-to-downstream direction, or the ideal panel observation point. The figurative engravings can be seen in the right direction, but the space is always located far away from and below the panel. Therefore, indirect lighting by grease lamp or torch was necessary to observe the panels (which were illuminated by another person standing next to the wall). Moreover, the large size of these panels requires either several light sources or displacement of the source.

Analysis of access to the panels on topographic maps

Cussac Cave is a corridor-like cave; therefore, there is often only one pathway near the panels, or occasionally two (meanders intersected). However, some areas are more complex (Jouteau et al. 2019), with three different kinds of behaviours, corresponding to the three groups highlighted above.

Group 1 panels are engraved on walls next to the natural pathway, especially where the gallery is narrow and without another accessible path. These pathways are always accessible without any difficulty.

Group 2 panels are located on ceilings above the natural pathway, so it is necessary to walk below them to move forward inside the cave. They are often low passageways above tiered and inclined grounds, making the conditions of access much more difficult than for group 1.

Group 3 panels, conversely, are often located outside the logical pathway, and some even required an extensive search for their support. They are located far above the pathway and sometimes required the engraver to climb in order to access the support while the potential observer was below the panel, often on a large section of the main pathway without any difficulty gaining access.

4. Contributions and constraints of the in-situ study

The study of both the database and topographic maps provides answers to the questions previously asked (Jouteau et al. 2019):

- Do the geology and geomorphology of the cave influence the location of the panels? Does this location depend on the type of panels?

Contrary to what is often observed in cave art, the motifs do not seem to include natural features in their lines. However, the much-preferred selection of massive limestone rather than layered limestone, especially in the third group, shows that the geological factor contributed to the choice of panel location. Nevertheless, this is not systematically the case; while the aspect of the wall influenced the choice made by the Gravettian engraver(s), other parameters also played a role.

- Which potential audience were they aimed at (Image-makers only? Viewers? A spiritual entity?)?

With their restricted fields of visibility and the use of layered-bed limestone for some panels, the question arises: were panels in groups 1 and 2 were intended for subsequent viewing or if the intention of the engraver(s) was to leave a trace on the rock. In the latter case, the purpose and use of these motifs would not require an audience. Mainly located at key points along the pathway, the group 2 panels may have served as both topographical landmarks and symbolic milestones within the spiritual journey experienced in the site.

On the other hand, engraved on visible parts of large galleries, on regular limestone, group 3 panels seem to point to the presence of an audience. The remaining question concerns the temporality of this audience: was the creation process performed collectively, or were these panels intended for subsequent viewing? Many panels in group 3 appear in their final stage as palimpsests which are very difficult to decipher. It is thus likely that viewers were present when the engravings were done, and perhaps only then, with the movements and gestures of the engraver(s), and possibly the storytelling, making the motifs more perceptible and the narrative more intelligible (Feruglio et al. 2019). This does not rule out subsequent visits that would have required prior knowledge of the panels' locations, and special lighting at the bottom of the panels to make them visible from a distance.

- How are the panels distributed throughout the cavity?

There is a clear opposition between the Downstream Branch, which contains panels from groups 1, 2 and 3 and has a high density of panels, and the area from the entrance to the 'cavicorn' panel in the Upstream Branch, where there are only group 2 panels and a far lower density of panels.

According to our previous hypotheses, these panels reflect the different ways in which the Palaeolithic group used and appropriated the space. The difference between the groups present in the Upstream and the Downstream branches can be interpreted either as different use of these areas; or as frequentation of these spaces by different groups of people — although these are not the only explanations. This opposition between the Downstream and Upstream branches is also reinforced by other features, like the presence of human remains in the Downstream Branch. However, this cannot be interpreted as the frequentation of these two areas at two different periods, because the styles and themes of the motifs (e.g. the presence of female representations or rare motifs such as birds or rhinoceros heads) are highly homogenous.

- Could these panels have played a different role in Palaeolithic use of the cavity?

The subdivision of the panels into three groups indicates that at least three kinds of behaviour or use of the cavity occurred in Cussac Cave. Although it has been assumed that a single rock art site could have played different roles (Lorblanchet 1982, 1995, 2010; Fortea Pérez 1994; Bourdier 2013), this study suggests that the role of cave art sites in these societies was even more complex. These hypotheses must nevertheless be viewed with caution, as the study of Cussac cave is still in progress and new elements could confirm or refute them in the future.

The combination of topographic maps and statistical analysis of the database provides interesting and complementary results, allowing us to propose interpretative hypotheses. Future phases of this research need to include graphical criteria such as the technical characteristics and formal traits of the representations in order to better understand the distinction between the three groups. Moreover, an exhaustive study of all the panels will be conducted when the whole cave is surveyed, which requires prior logistics work to equip the pathways.

Additionally, we have noted two main limits to the in-situ study. The first one is our limited pathways, which led us to extrapolate to some visibly inaccessible areas. The second is that all our observations were made with modern headlamps, producing very powerful lighting compared to Palaeolithic light sources (mainly grease lamps and torches). It is also directional lighting, which induces a considerable bias in the legibility of engravings, whereas Palaeolithic lighting was omnidirectional.

IV. Presentation of the ex-situ method: simulation tools[1]

1. Interest

In a context of increasingly restricted access to cavities, the use of three-dimensional surveys in the study of decorated sites is commonplace, when it is possible. To date, there are two primary uses:

- High-precision three-dimensional surveys on small areas to examine details (prints, or lines) without being on-site. This makes it possible to vary the light or the viewpoint of the observer.
- Surveys of entire caves, or parts of caves, for conservation or replication purposes (simulation of thermo-aeraulic flows, facsimile).

In this study, we aim to investigate what three-dimensional surveys of large portions of caves can contribute to the scientific study of these caves. We intend to use one of the specificities of the three-dimensional survey, which is to provide a basis for the simulation of different lighting or sound environments. In the previous study, we observed that our limited access and modern lighting were bias in our interpretation of the areas of visibility, Palaeolithic access, and everything related to the interpretation of the surroundings. The use of three-dimensional surveys is in itself a solution to compensate for our limited access, but the lighting offered by most visualisation software is not designed to be realistic, let alone be compared to Palaeolithic lighting. That is why we plan to test the contribution of lighting simulation tools.

In our society, we mainly use our eyesight to find our way around in space, and this is reflected in the use of very powerful headlamps in caves to orientate ourselves. However, some authors have suggested that Palaeolithic people may have been able to use their hearing to orient themselves (echolocation), as their lighting may not have been sufficient (Reznikoff 2010). To test this hypothesis in the light of modern tools, we also seek to simulate sounds.

2. Lighting simulation software

Lighting considered

Four Palaeolithic lighting devices are known. The first, the grease lamp, is known thanks to the discovery of greasy or charcoal residues associated with sandstone and limestone lamps, as well as reddening marks attesting to the heating of the lamp. Grease lamps have been found in many decorated caves, including Cussac (two specimens to date) and Lascaux (between 36 and 130 lamps, according to estimations; Delluc and Delluc 1979); this is the first lighting that we reproduce. Previous studies have been carried out on the reproduction of Palaeolithic grease lamps (Delluc and Delluc 1979; de Beaune 1983, 1987; de Beaune and White 1993; Collina-Girard 1998). These experiments show that lichens, mosses and juniper twigs make the best wicks. The fats used derive mainly from modern animals such as bullocks or horses, and this induces a bias because such animals are dissimilar to those that lived during the Palaeolithic. Seal oil and moose marrow were also tested by de Beaune (1983, 1987, 1993). These experiments, although incomplete (no spectrum measurements have been made, for example), reveal that seal oil offers the best flame (more stable and powerful), that marrow fat yields the worst flame, and that subcutaneous fat from beef and horsemeat are roughly equivalent and of intermediate quality. Most of them provide light as powerful as a modern candle.

The second, the torch, is also a mobile light, of which only indirect traces have been found in decorated caves: torch smears and charcoals (Medina Alcaide et al. 2015). These are carbonaceous residues resulting from a torch rubbed against a wall in order to rekindle its flame. This leaves a visible trace which may also have been used as a topographic landmark (Medina Alcaide 2015; Groenen 2016). These remains can be found in many decorated caves, including Cussac, where two samples were taken for dating and analysis. The analysis shows that at minimum *Pinus* (mainly *sylvestris*) and juniper were used to make torches (Medina Alcaide et al. 2015). Experiments on this question are scarce, and do not allow a comparison of the various devices and raw materials, nor do they offer physical measurements concerning the duration of the lighting, its spectrum or its intensity.

The third lighting source recognised as a Palaeolithic source is a fireplace. This light source is fixed, but its intensity is adjustable since this intensity depends only on the quantity of fuel. The fireplace can also be used for heating (food, pigments and other). Fireplaces of varying sizes have been found in Palaeolithic decorated caves, but no evidence of a fireplace has been found so far in either Cussac or Lascaux, which is why this lighting source will not be reproduced in the first part of the study.

Finally, fixed lamps have been discovered in rare cases, the best-known examples of which are in Nerja (Andalusia; Medina Alcaide et al. 2012). Neither Cussac nor Lascaux have them, which is why this type of lighting will not be considered in the first stage of this study.

Physical measures and bias

When a surface is illuminated, three factors are involved: the physical characteristics of the source (e.g. flux, intensity, spectrum), the surface (e.g. reflection coefficient, texture information, spectral response), and finally the observer's eyesight and experience. The latter factor is, of course, more challenging to reproduce, especially in digital simulations where the conditions of observation are not the same as at the scene, and where the presence of a screen of unique brightness and colour management causes additional bias if it is not calibrated. That is why we decided, in the first step, to focus on the calibration of the first two factors.

1 The study presented here is under development, so we do not present results, but only the initial set-up of analytical tools.

Light sources (grease lamps and torches) will be created and then measured outdoors (to limit the influence of the light reflected from possible walls) at night-time, using a spectroradiometer. The physical characteristics thus measured will be the flux (in lumen), intensity (in candela) and the emitted spectrum.

The measurement of wall and floor characteristics will consist of in-situ measurements using a spectroradiometer. As exhaustivity will be impossible, the walls and floors will be selected according to their accessibility and representativeness. This phase can be done in Cussac but not in Lascaux, which is inaccessible. However, additional measurements in the experimental Leye cave (Marquay, Dordogne, France), which is fully accessible for research (Lacanette et al. 2013), should allow us to calibrate our models.

Finally, an on-site survey will be possible at Leye cave. This might allow us to compare what appears on the screen with what we really perceive and adjust our models accordingly if necessary.

Software description

PHANIE software is a tool to simulate lighting based on spectral data. It is based on the ray-tracing technique used to provide several methods for simulating light phenomena (e.g. path monitoring method, radiosity, photon map) in order to evaluate the illumination or colour rendering of a scene based on a three-dimensional survey with a complex morphology.

We have chosen to use this software rather than freeware that can also simulate artificial lighting (Blender, for example) because PHANIE can integrate all the physical characteristics (of sources and walls) involved during lighting. Also, the software offers interesting functionalities such as the ability to simultaneously integrate several sources with different characteristics or to move them with the observer during sequences of several images.

For the software to include the characteristics of the walls, the measurements must be implemented in the three-dimensional survey before the calculation. This requires a division of the survey into areas associated with measurements, hence the importance of choosing the samples to be measured. The characteristics of the sources are placed in a database and integrated during the calculation.

The software offers a photorealistic rendering in an image, a sequence of images or a scene in which it is possible to move a camera freely (these three types of rendering depend on the method used, which also influences the calculation time and the accuracy of the results), and a false colour rendering with a scale of magnitudes. The photorealistic rendering offers a better immersion in the scene and a more intuitive interpretation but is highly dependent on the observer's visual abilities and screen (which therefore requires prior calibration). The false-colour rendering is less intuitive but provides objective measurements, independent of the observer, the screen or the paper printout.

The main limitation of the software lies both in the precision of the three-dimension survey, which does not allow the finest details of the engravings to be considered, and in the extrapolation of a few measurements to the entire cavity, overlooking any unusual features. Integrating a different reflection coefficient between the surface of the walls and the engravings is theoretically possible, but requires heavy calculations, which we do not plan to integrate until this first phase is completed.

3. Acoustic simulation software

Physical measures and bias

As for lighting, three physical factors are involved when emitting sounds and listening to them: the characteristics of the sound emitted (power, frequency), the walls on which they are reflected (acoustic energy absorption coefficient), and the ears of the receiver. As the latter is unique for each individual according to his or her physical condition, age, experience and culture, it will not be included in our study. Instead, 'standard' ears, i.e. average results of measurements on a set of individuals, will be used.

To identify the characteristics of the sound used, it must be recorded under anechoic conditions (in a room which completely absorbs sound waves). The human voice is the first range of sounds considered in this study, because it is universal, used in all human societies, and more appropriate for the discovery of space than an instrument that might be oversized. Many human voices have been recorded under such conditions and are freely available on the Internet. In a second step, recording instrumental sounds under such conditions is possible. These would be instruments certified for the Palaeolithic period, such as flutes, whistles, musical bows or rhombuses. However, choosing, creating and recording these sounds requires an investment that we will only consider once the methodology has been developed and calibrated using human voices.

The measurement of the material's response to sound stimuli will be done in two steps. Samples of various materials will be sent to the Centre Scientifique et Technique du Bâtiment (Scientific and Technical Centre for Building) for measurement in Kundt's tube. This will provide us with the normal impedance and the acoustic energy absorption coefficient of the material. Five materials will be measured: three representative limestones from Lascaux, Cussac and Leye caves, calcite, and clayey sediment, chosen for its grain size similar to that of the sediments present at Cussac cave. The limestone samples were collected on blocks from excavated material for Cussac and Lascaux caves and within Leye cave itself.

In a second step, in-situ measurements of the impulse response (IR) will make it possible to calibrate the sound decay, diffusion, and the theoretical response relative to the real response. This measurement will not be possible in Lascaux, which is why we will carry it out in Leye cave. The measurements at Leye and Cussac will allow a calibration which is potentially applicable to Lascaux. It will also be possible to do sound tests in Leye that can be compared with what we get with the software to check the quality of our calibrations.

Software description

ICARE (Noé et al. 2009, 2011) is a tool to simulate acoustic propagation in complex three-dimensional environments (such as cave walls, which are not flat surfaces). It allows the calculation of reflection and diffraction effects between a source and a receiver in any type of environment by combining two methods (beam tracing and particle tracing).

We chose to use this software because it can manage complex environments while allowing us to customise the characteristics of the walls. As with PHANIE, the wall characteristics must be integrated into the three-dimensional survey before calculation by segmenting the survey into zones associated with sample measurements. The sources are integrated during the calculation.

This tool provides both auralisation, i.e. the binaural sound reproduction of a sound recorded under anechoic conditions, and the impulse response of the surroundings (which depends only on the characteristics of the environment). The latter enables the extraction of criteria that can characterise the acoustics of a space, such as reverberation time or voice clarity, which makes it possible to objectively compare the acoustics of different spaces (regardless of the sound emitted). The binaural response is a stereo response that considers HRTF (head-related transfer functions), which are directional functions characteristic of human ears (including head and torso effects). Intended for headphone listening, this response serves to reproduce the spatial location of the different echoes according to the orientation of the head.

The main limitation of the software lies in the extrapolation of some measurements to the entire cavity and points, once again, to the importance of the choice of samples to be measured.

4. Intended applications

As Cussac and Lascaux caves are very different in many respects, different applications are intended. The idea is not to be exhaustive in the questions we are considering but suggesting some possible approaches where we think the use of previous tools would be relevant.

Lascaux cave

Lascaux cave is not accessible for research of this type, but its three-dimensional survey is complete and fully textured, and we have obtained permission to use it. Leye cave will be used to validate our models, for example, by comparing what we measure in situ with what we obtain via the simulation tools. This step is all the more essential as it will be impossible to carry out these checks in Lascaux cave.

The survey represents the cave in its current state, i.e. with its modified grounds, the presence of artificial benches, and the modern entrance with doors. However, a project is underway to reconstruct the grounds at the time of discovery and then in the Palaeolithic (project MicroPaGO, dir. D. Lacanette, IdEx funding, then Ministry of Culture). These reconstructions should allow tests to be performed on the influence of ground height on acoustics or lighting. The Palaeolithic entrance should also be reconstructed according to different hypotheses about its Pleistocene size and morphology. It will then be interesting to simulate natural outdoor lighting to determine how far daylight could illuminate the interior of the cavity, according to these different hypotheses. This question is all the more interesting as the first decorated room, the Hall of the Bulls, is located about twenty metres from the current entrance.

Lascaux cave is particularly well-known for the gigantism of some of its animal representations, with the largest currently known bulls represented in Palaeolithic art (the longest is 5.5 m long). It would, therefore, be interesting to simulate different lighting to understand which kinds of light sources, and how many, were needed to illuminate it as a whole. The same question can be asked about the whole room, whose graphic continuity over a 20 m long and approximately 6 m wide rotunda raises the question of its lighting: could the whole room be fully illuminated, and how?

The cave ceilings are mostly made up of large domes; do they influence the acoustics of the place?

No sediment samples composing the Lascaux Palaeolithic grounds are accessible, which is why we will not be able to measure the acoustic energy absorption coefficient or the reflection factor. However, it will be possible with simulation tools to test different materials and to verify their influence on the lighting or acoustic qualities of the place, based on the geological data from the research carried out in the cave (Leroi-Gourhan and Allain 1979).

We see that, as a first step, it will be necessary to test the influence of parameters that we do not have (e.g. ground morphology and nature, the opening of the entrance porch). Secondly, if the influence of these parameters does not seem too significant, it will be possible to address archaeological issues such as the lighting methods for large frescoes or the acoustic qualities of the site and their influence on the organisation of the wall decoration or the possibilities for the Palaeolithic people to orientate themselves using echolocation.

Cussac cave

The cave of Cussac is accessible to on-site studies only for a few weeks a year, and the pathway inside it is restricted to a 50 cm-wide walkway. However, at present, a three-dimensional survey of the cavity is only available from the entrance to 200 m downstream, near the Headless Cervid, and it is textured only over about 50 m, from the Discovery Panel to Locus 2.

The textured part is limited, but contains three panels (panels of the Discovery, Clay Bridge and Toupillon) and will serve to compare our results with those of the first in-situ study, in particular concerning the visibility fields of the panels, the number and kinds of lighting necessary to illuminate each panel or the recognition of the paths used by Palaeolithic people. The acoustics in this part of the cave can also be compared to an on-site study conducted by voice and ear.

For example, the presence of a fireplace or a torch on the ground at the bottom of the Discovery Panel, allowing the engraver to light the surface, has been proposed as a hypothesis. So the simulation of a fireplace at this location could provide new elements.

Human remains in Loci 1 and 2 are located near the current pathway in the cavity and are very easily visible, but is this the case when grease lamps or torches are used to move around?

The confirmed presence in Cussac of grease lamps and torches raises the question of the complementarity of these two lighting systems: is one more suitable for displacement and the other for the static position (used when creating engravings or observing them)?

Do the best viewing areas of the panels also correspond to the areas from which the sounds produced in their vicinity are best heard? What is their scope? Is the place more appropriate for the spoken voice, sung voice, or is the reverberation so great that it will cause discomfort? Do the panels occur at the point where the sound effects change?

In general, we plan to carry out an in-depth study on the lighting and acoustics of this part of the cavity until other areas are textured.

V. Conclusion

As presented in this paper and previously (Jouteau et al. 2019), a field study combining both a statistical study of a database and topographic maps provides interesting results and a deeper understanding of the appropriation of the subterranean environment by Palaeolithic groups. Although our study is still ongoing, with a selection of the studied panels and the absence of some significant graphic criteria in the database, three different behaviours inside Cussac cave have already been highlighted. This is very promising, and the intention is to continue this study by integrating more graphic criteria and more panels into the Cussac study before applying this method to other caves, which will offer a better understanding of the behaviour and objectives of Palaeolithic people when they occupied the underground environment.

However, this type of study comes up against the limited accessibility of the site (impossible in some cases, e.g. Lascaux, limited in time in others, e.g. Cussac), the restricted walkways inside the site (with inaccessible cave portions, e.g. most of the Upstream Branch of the Cussac cave), and our perception of the place, biased by possible anthropic modifications (e.g. the floors in Lascaux cave) or natural ones (more partially for Cussac with a thin deposit of clay, new concretions and other factors) and by the use of modern, directional, very powerful white-light headlamps.

The use of lighting and acoustic simulation tools in a survey based on the assumed morphology of the cave during the Palaeolithic period would make it possible to compensate for these limitations.

However, as we have shown, the use of these tools must be preceded by a phase in which the physical properties of the selected sources and materials present in the site are measured (normal impedance, acoustic energy absorption coefficient, sound decay, diffusion for the acoustics simulations, and reflection coefficient and spectral response for the simulation of light). This stage, which will be the next step in our work, requires on-site intervention. When such intervention is not possible (for example, in Lascaux cave), it is imperative to perform the measures and the calibration in an entirely accessible cave such as Leye to validate the simulations.

Moreover, it seems essential to conduct a field study beforehand in order to determine the questions on which the simulations can complete the field study. This phase of on-site investigation (when possible) is all the more critical as each decorated cave is unique in its morphology, its parietal decoration, as well as its natural or anthropic alterations. Thus, the relevant applications will be different for each one, and it will be necessary to adapt the way simulations are used to each case.

Simulation tools seem to have become increasingly necessary as the conditions of access to and within sites have become more restrictive, although these tools are not a complete substitute for field studies, as they require on-site measurements at minimum. Their main benefit lies in simulating the physical and technical conditions in place when Palaeolithic people discovered and occupied these spaces, bringing complementarity to field studies.

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Armance Jouteau[a*] (PACEA), Valérie Feruglio[a] (PACEA), Delphine Lacanette[b] (I2M), Samuel Carré[c] (CSTB), Nicolas Noé[c] (CSTB), Jacques Jaubert[a] (PACEA)

[a] PACEA Université de Bordeaux, UMR 5199, b02, Avenue des facultés, 33615 Pessac Cedex, France
[b] I2M Université de Bordeaux - UMR 5295, 33600 Pessac, France
[c] Centre Scientifique et Technique du Bâtiment (CSTB), 11 rue Henri Picherit, 44000 Nantes, France
* corresponding author
armance.jouteau@u-bordeaux.fr, feruglio@free.fr, lacanette@enscbp.fr, samuel.carre@cstb.fr, nicolas.noe@cstb.fr, jacques.jaubert@u-bordeaux.fr

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RAR 37-1331

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