



# Drawing in the depths: spatial organization patterns related to Magdalenian cave art

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## Abstract

The creation of rock art in the deep areas of caves was one of the most unique symbolic activities of Magdalenian societies in southwestern Europe between 13.5 and 21 thousand years ago. Previous research has suggested that these works of art were not placed in caves at random but rather their location corresponds to a pre-established structure. However, despite the suggestive idea of pre-planning the decoration of the endokarst, it is challenging to demonstrate the relationship between different works and between them and their immediate spatial context due to the lack of common objective criteria. In this study, we have examined the iconographic and spatial characteristics of 500 Magdalenian graphic units in nine caves in the Cantabrian and Pyrenees mountain ranges (southwestern Europe) to identify patterns of graphic construction based on their cave location. We designed a workflow that includes geomorphological analysis for a virtual reconstruction of the state of the caves during the Magdalenian, analysis of graphic units (GU) through geographic information systems (GIS) using a Python script, and multivariate statistical study of the spatial and iconographic parameters of these figures. This has allowed us to identify different groups of figures: some were specifically created to be seen, using various techniques and selecting locations with good visibility, accessibility, or capacity to accommodate people, while others sought the opposite. There is also a correlation between the techniques used and their location in caves, perhaps aiming for resource economization. These data support the existence of different uses for the deep sectors of caves during the Magdalenian period.

**Keywords** Palaeolithic · Rock art · GIS · Script · 3D · Statistics

## Introduction: The exploration of deep caves by Magdalenian societies

The Magdalenian is the name given to one of the Palaeolithic cultures that developed in southwestern Europe after the last glacial maximum, between 13.5 and 21 thousand years ago (Breuil 1912; Utrilla 1981, 1984/85; González Sainz 1989; Langlais et al. 2010; Ducasse et al. 2011; Angevin 2012; Bicho and Haws 2012; Román and Villaverde 2012; Pétilion 2013; Langley et al. 2016; Bourdier et al. 2017; Ivanovaité et al. 2020; Maier et al. 2020). One of the most striking characteristics of this period is the strong thematic and stylistic unity observed in graphic expressions, spanning the

Cantabrian coast, the Pyrenees, and Aquitaine during this period (Forte 1983, 1989; Forte et al. 1990; Fritz et al. 2007, 2016). This coincides with networks of material, cultural, and technological exchange (Conkey et al. 1980; Tarrío et al. 2015; Gravel-Miguel 2016; Martín-Jarque et al. 2023), shared among even more distant regions, such as the Mediterranean coast or the European Steppe (Bahn 1982; Langlais et al. 2016; Ducasse et al. 2019; Sánchez de la Torre et al. 2020, 2023; Jöris 2021; Lefebvre et al. 2023; Marsh and Bello 2023). This globalization process may have been motivated by a population increase following climatic stress between 21 and 24 thousand years ago (García-Moreno 2013; Tallavaara et al. 2015; Fu et al. 2016; Villalba-Mouco et al. 2019, 2023; Posth et al. 2023).

The exploration and symbolic appropriation of deep caves through the creation of cave art stand out among the most distinctive symbolic activities carried out during the Magdalenian period. Notable examples include Rouffignac, Niaux, or Tuc d'Audoubert. In fact, the conquest of caves beyond the threshold illuminated by sunlight became a reference

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point in human evolution, with some authors including it among the milestones in the emergence of behavioural modernity (d'Errico 2003; Marquet et al. 2023), with earlier precedents dating back to the Middle Pleistocene in Bruniquel Cave (France) (Jaubert et al. 2016).

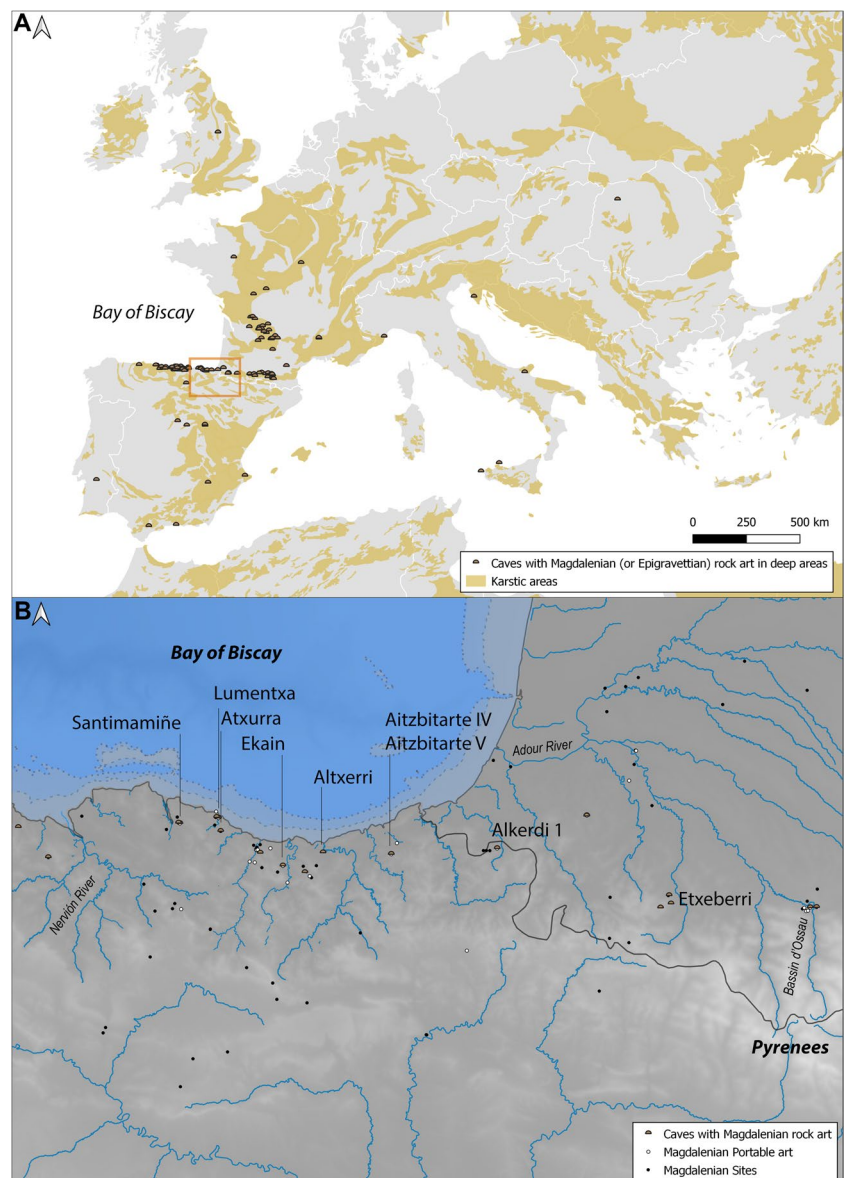
During the Upper Palaeolithic, this phenomenon mainly took place in Europe, specifically in the area surrounding the Bay of Biscay (Lorblanchet 1995; Clottes 2012, 2013; Garate 2018). It is surprising to note that this region coincides with the highest dispersion and cultural unity during the Magdalenian, with an almost total correlation between the presence of karst landscapes and the existence of decorated caves. Currently, for this chronology, about 150 caves with cave art in deep sectors requiring the use of artificial lighting are known in Europe (Medina-Alcaide et al. 2021). This contrasts, for example, with the quantity and dispersion

of decorated caves known for other contemporaneous cultures, such as the Epigravettian (Fig. 1).

All of this indicates that the decoration of deep caves was an essential part of the symbolic activity of Magdalenian societies around the Bay of Biscay, in addition to rock art in dimly lit areas (shelters or cave entrances) and in the open air, as well as portable art and other activities (rituals, dances, songs, music) that left few visible traces in the archaeological record (Buisson 1990; d'Errico et al. 2003; Higham et al. 2012; Fritz et al. 2021). Given the recurrent nature of this activity, studying the position of art inside the cave is of great interest to understand its motivation (Bahn 2011).

However, despite the repeated use of cave forms to enhance some of the figures being noticed from the early days of the scientific discovery of this cultural phenomenon

**Fig. 1** (A) Map of the Southeast Europe showing the location of caves containing Magdalenian cave art in deep areas, comparing them with karstified zones. In the orange rectangle, we present the enlarged image in Fig. 1.B. (B) Map of the region between the basins of the Nervión and Adour rivers (up to its Bassin d'Ossau branch), displaying the location of Magdalenian sites and marking the caves analysed in the present study. We have positioned the sea level 100 m below the current level, in light grey and points, representing the level during the Last Glacial Maximum at the beginning of our period of interest (approximately 21–24 ka), and the sea level at the end of the Magdalenian in dark grey and strokes (around 13.5–14 ka). The current coastline is indicated in black. (Data source for the Digital Earth Model: <https://www.gmrt.org/GMRTMapTool/>; Administrative data source: [https://gadm.org/download\\_country.html](https://gadm.org/download_country.html) and <http://www.euskalgeo.eus/es/node/157>; Source for Karst maps: <https://data.europa.eu/>)



in Altamira Cave (Sanz de Sautuola 1880), no specific study was conducted on spatial-related issues. There were disagreements about the technology of these societies and their ability to access these places so far from the outside (e.g., Harlé 1881; Puig y Larraz 1896; Rivière 1897). Influenced by ethnographic comparisons with tribal societies, some authors attributed magical and ritual significance to cave art and pointed to the fact that many motifs were in the dark depths of caverns as evidence that they were only accessible to certain initiates (Reinach 1903; Breuil 1905; Alcalde del Río et al. 1911). In any case, it was not until the mid-20th century that the role of the cave as a whole in the structure and composition of prehistoric art began to be discussed (Raphaël 1945, 1986; Laming-Emperaire 1962; Leroi-Gourhan 1965). However, one of the main problems with these pioneering investigations was the subjectivity derived from the necessary use of qualitative terms, hindering objective comparisons between different sites. The conclusions drawn by each author were significantly different, sometimes even contradictory, partly due to the measurement techniques used, often limited to the empirical knowledge of the researcher, with the inaccuracies that come with it.

To overcome these problems, some authors proposed applying semiotics and formal and computational linguistics to the study of cave art (Sauvet et al. 1977; Sauvet 1988; Sauvet and Włodarczyk 1995). Assuming that cave art conveyed collective thought, it should be structured like any other communication system or language (e.g., Luquet, 1926; Leroi-Gourhan 1964, 1967; Sanchidrián 1991/92; Etxepare and Irurtzun 2021). This allowed a more precise comparison of the iconographic characteristics of parietal figures. However, spatial parameters continued to be studied with qualitative methods, although there were numerous interesting proposals in this regard (Rouzaud 1978, 1990, 1997; Vialou 1986; Penton 1990; González García 2001; Villeneuve and Hayden 2007; Villeneuve 2008; Pastoors and Weniger 2011; Ochoa 2017; Ochoa and García-Diez 2018; Gittins and Pettitt 2017). In recent years, these problems have been partly resolved by the use of digital methods that have made spatial analyses more accurate.

On one hand, multivariate statistics have enabled interesting advances in studies of cave art based on its location in the cave (Jouteau et al. 2019). On the other hand, with spatial measurement software, such as Geographic Information Systems (GIS), and 3D technology, it has been possible to obtain comparable quantitative data across different sites (Jouteau et al. 2020; Jouteau 2021; Intxaurbe et al. 2020, 2021, 2022; Wisher et al. 2023a).

In this study, we analyse whether the graphic repertoire of caves decorated during the Magdalenian is conditioned by the spatial characteristics of the cave. That is, we will try to answer whether accessibility difficulties or visibility influence the graphic characteristics (theme, technique, format,

and size) of the depicted images. In other words, whether Magdalenian cave art responds to a multifunctional communication system, at least concerning the use of dark sectors within caves. To do this, we will use a methodological flow that combines prior geomorphological analysis and 3D technology (allowing us to reconstruct the caves known to these Palaeolithic societies), the use of Geographic Information Systems (GIS) in three-dimensionally complex environments, and multivariate statistical analysis that allows the analysis of qualitative and numerical variables.

## Materials: Magdalenian cave-art (13.5–18.5 ka) around the central Bay of Biscay

As previously mentioned, the territory surrounding the Bay of Biscay maintained strong cultural cohesion, especially during the Magdalenian period. In fact, the area between the Nervión River as the western limit and the Adour River (up to its Bassin d'Ossau branch) as the eastern limit acted as a hub for interregional communication. This was due to its strategic location between the Iberian Peninsula and the rest of the European continent, as well as being one of the two main natural corridors round the Pyrenees. In this sense, it is not surprising that it is a territory with a high density of archaeological sites of Magdalenian chronologies (González Sainz 1989; Dachary 2002; Arribas Pastor 2005; González-Sainz and Utrilla 2005; Garcia-Moreno 2013), sharing technological and cultural traditions characteristic of more distant geographic regions (e.g., Utrilla 1986; Arrizabalaga 2007; Garate et al. 2015a).

Currently, in this territory, 38 caves with Palaeolithic rock art are known (Garate 2018; Garate et al. 2020a), several of them with decorated sectors of very difficult access. Of these, 21 were decorated during the Magdalenian, although in Aitzbitarte V (Garate et al. 2020b) and Erberua (Larribau 2013; Garate et al. 2020c), rock art from older chronologies also coexists. In our study, we have analysed nine of these caves (Fig. 1), whose chronology has been estimated based on stylistic comparison with datable portable art pieces from stratigraphy, as well as the contextual dating of archaeological elements in spatial relation to the rock art. To validate contextual dating, coherence has been found between the two methods, suggesting that the art in the studied caves was created between 18.5 and 13.5 thousand years ago (Supplementary Materials).

There are another 12 decorated caves in the region with Magdalenian art, which have not been included in the study due to the lack of three-dimensional scans and/or recent geomorphological studies that would allow for their virtual reconstruction (Intxaurbe et al. 2023), an indispensable milestone as will be seen later. Several of them (Morgota, Arbil V or Sustraixa, Astuigaina, Sasiziloaga,

and Sinhikole) present very discreet sets, sometimes fewer than half a dozen figurative representations. This typology of “minor sanctuaries” can be represented with the inclusion in this work of Lumentxa or Aitzbitarte V. On the other hand, almost all the medium and large-sized “sanctuaries” (with more than 10 figurative representations) in the region have been included in this study. Only the sites of Armintxe, Otsozelaia, and Erberua have been excluded from the study. The latter would be one of the great sanctuaries of the region with at least 115 figurative representations (Garate 2018). The reasons why these caves could not be included have been summarized in the following table (Table 1).

In any case, the caves not included in the present study contain a total of 236 (+ 15 doubtful) figurative representations, accounting for 32.07% of the total figures in the region, a quantity lower than the 500 studied in this work, which represent 67.93% of the total corpus of figurative graphemes in the region (see Table S2 in Supplementary Materials). Both figurative representations (zoomorphic and anthropomorphic) and various types of signs (points, paired strokes, meandering strokes, rectangles, projectiles, crosses, and a possible claviform) have been selected. Other undefined or very simple elements have been excluded from our study due to the impossibility of ensuring expressive intent (formless stains, stigmas of loose lines, etc.) and a specific chronology.

## Methodology: Between GIS and statistics

As previously indicated, digital technology allows precise quantitative analysis, applying the same criteria to all subjects under study. Previous studies validate the use of GIS (e.g., Intxaurbe et al. 2020, 2021, 2022), multivariate statistics (e.g., Jouteau et al. 2019), and 3D technology (e.g., Jouteau et al. 2020; Jouteau 2021; Wisher et al. 2023a) in the study of cave art based on its arrangement in the cave. In this study, we will attempt to combine these methods to objectively analyse Magdalenian cave art in the central Bay of Biscay region.

## Geometric documentation of endokarstic morphology by terrestrial laser scanner (TLS)

The studied caves were scanned between 2008 and 2022 by the companies Virtualware (Barrera 2008; Barrera and Bayo 2010; Iturbe et al. 2018) and GIM Geomatics (Bayarri et al. 2021). Initially, a point cloud was generated using various types of laser scanners (technical specifications for each case can be found in Section S3 of Supplementary Materials). In general, reference spheres and targets were used to link the scans (Sadier 2013; Jaillet et al. 2014, 2017; Genuite et al. 2023), in addition to precise georeferencing and orientation of the point cloud using a Global Navigation Satellite System (GNSS) (Bayarri et al. 2021). Subsequently, models (3D meshes) were created using *CloudCompare v2.13*

**Table 1** Caves with Magdalenian art in the study region that have not been included in this study, showing the number of figurative representations (we have also included complex abstract representations, including dots). In parentheses, we indicate some doubtful represen-

tations that would increase the corpus. We also note if they contain 3D scans or recent geomorphological studies, essential for virtually reconstructing the underground landscape and analysing the spatial context correctly and precisely

Caves	N° figurative representations	3D model	Geomorphological studies	References
Morgota (Kortezubi, Bizkaia)	1 (2–3?)	Yes	Partial	Garate et al. 2015b
Armintxe (Lekeitio, Bizkaia)	59	Partial	Partial	González Sainz 2019/20
Goikolau (Berriatua, Bizkaia)	1 (2–3?)	No	No	González Sainz 2021
Arbil V or Sustraixa (Deba, Gipuzkoa)	2 (3?)	No	No	Antxieta Arkeologi Taldea et al. 2018
Astuigaina (Zestoa, Gipuzkoa)	2	No	No	Ochoa et al. 2020
Isturitz (Isturits/Saint-Martin-d’Arberoue, Nouvelle-Aquitaine)	15	Yes	Partial	Garate et al. 2016b
Oxocelhaya (Saint-Martin-d’Arberoue, Nouvelle-Aquitaine)	40	Partial	Partial	Garate et al. 2017
Erberua (Isturits/Saint-Martin-d’Arberoue, Nouvelle-Aquitaine)	ca. 108 (only magdalenians)	No	No	Larribau 2013
Sasiziloaga (Aussurucq, Nouvelle-Aquitaine)	2	No	No	Garate and Bourrillon 2017
Sinhikole (Camou-Cihigue, Nouvelle-Aquitaine)	4 (5?)	No	No	Garate and Bourrillon 2017
Sainte-Colome (Arudy, Nouvelle-Aquitaine)	4	No	No	Garate et al. 2013a
Saint-Michel (Arudy, Nouvelle-Aquitaine)	(1?)	No	No	Garate et al. 2021



software with an average resolution of 0.05 m for each cave (Intxaurbe et al. 2023).

### Geomorphological analysis

The caves were studied geologically to identify the stratigraphic units that shaped the current topography. Sedimentation and erosion events were stratigraphically correlated, and in some cases, radiometric dating using the uranium series (U/Th) method was employed to achieve greater precision in the chronological characterization of stratigraphic units (Arriolabengoa et al. 2020; Intxaurbe et al. 2023). Finally, the models were edited with *Blender 3.3.0* and *MeshLab 2022.2* to depict an appearance as close as possible to how each cave would have looked at the time when they were frequented and decorated between 13.5 and 18.5 ka. This involved relying on the results of geomorphological studies and, in some cases, utilizing historical documentation to enhance effectiveness (Intxaurbe et al. 2023). Such studies are essential to support the validity of archaeological interpretations based on the analysis of the modern spatial context (Delannoy et al. 2010, 2020; Genty et al. 2011; Canti and Huisman 2015; Verheyden et al. 2017; Arriolabengoa et al. 2020; Genuite et al. 2021, 2023). The specific results for each cave can be found in Section S4 of Supplementary Materials.

### Graphic documentation of rock art through photogrammetry and a database

Photographic and photogrammetric documentation of the documented figures has been generated from the most updated catalogues for each cave, as well as from revisions where new evidence has been discovered. Information regarding the number of graphic units (GUs) studied in each cave can be found in Section S2 of Supplementary Materials. Additionally, a database was filled out, to generate the table analysed with multivariate statistics (see below). For this purpose, a series of iconographic variables were determined (Table 2), and a table was created with the information for each of the 500 GUs (the complete table can be consulted on <https://github.com/inakiintxaurbe/spatial-organization-patterns-related-to-magdalenian-cave-art>).

Subsequently, each of the GUs was graphically documented using a data capture workflow described in previous works (Rivero et al. 2019; Salazar et al. 2019). That is, photographic captures of panels with rock art, as well as isolated figures, were taken, and these were converted into digital three-dimensional facsimiles using the Structure From Motion (SfM) technique. The software used for this was *Photoscan™ 1.2.0.2152* from *Agisoft®*. Once the mesh was created, it was georeferenced in the same

photogrammetric software, using targets whose coordinates were estimated from common points identifiable in the geolocated point cloud extracted from the preceding step (geometric documentation of caves with TLS). Once the photogrammetric models were correctly oriented, the graphic units were trimmed using *MeshLab 2022.2* software (Fig. 2). The goal was to obtain a three-dimensional facsimile for each GU. This was saved in .wrl format for subsequent analysis through GIS (see below).

### Spatial analysis using Geographic Information Systems (GIS)

The figures were analysed through Geographic Information Systems (GIS), using ArcGIS® software, specifically *ArcMap™ 10.5* for spatial analyses and *ArcScene™ 10.5* for visualization. The edited cave models and individualized Graphic Units (GUs) obtained in previous steps were imported into these GIS, with the models in .wrl format. This process followed a workflow described earlier (Scott and Janikas 2010; Opitz and Nowlin 2012). To measure spatial factors, a new Python script was designed, combining accessibility analyses (Intxaurbe et al. 2021), space visibility and capacity analyses (Intxaurbe et al. 2022), along with new measurements of relevant data: artist's estimated position based on the most comfortable area according to the slope, distance to the ground from the figure, and artist's posture according to measurements estimated by previous authors (Ochoa and García-Diez 2018). The estimated heights of the creators of the engravings and possible spectators were chosen based on height estimates from available human remains for the end of the Upper Palaeolithic and the beginning of the European Mesolithic, with an average of 159.90 cm: 165.3 for men and 154.5 for women (Holt 2003; Shackelford 2007 -increasing to 161.4 cm-; Cox et al. 2019). These sizes align well with the estimation of  $159.99 \pm 2.7$  cm for the nearest complete female individual to our study area, from the Lower Magdalenian, in Mirón Cave (Carretero et al. 2015). The script is available on <https://github.com/inakiintxaurbe/spatial-organization-patterns-related-to-magdalenian-cave-art>, and a more detailed description can be found in the Supplementary Materials Sect. 5. Due to the impossibility of uploading the files used to analyse the 500 GU, some partial files can be consulted at the following link: [https://github.com/inakiintxaurbe/GIS\\_Test\\_Santimami-e\\_Old\\_Chamber\\_of\\_Paintings](https://github.com/inakiintxaurbe/GIS_Test_Santimami-e_Old_Chamber_of_Paintings). It is noteworthy that, to standardize analysis criteria, torch lighting has been selected as a reference for calculating the visibility of the figures (Medina-Alcaide et al. 2021). The variables studied, together with their analysis criteria, are as follows (Table 3).

**Table 2** Table of the analysed iconographic variables for each Graphic Unit (GU). \* The complete table with the information for each GU can be consulted on <https://github.com/inakiintxaurbe/spatial-organization-patterns-related-to-magdalenian-cave-art>

Variable	Values	Meaning
Theme	Bison	Bison
	Horse	Horse
	Ibex	Ibex
	Hind	Hind
	Deer	Deer
	Reindeer	Reindeer
	Chamois	Chamois ( <i>Rupicapra rupicapra</i> )
	Saiga	Saiga antelope ( <i>Saiga tatarica</i> )
	Bear	Bear
	Aurochs	Aurochs ( <i>Bos primigenius</i> )
	Salmon	Salmon
	Flounder	Flounder
	Fish	Indeterminable fish
	Hare	Hare
	Fox	Fox
	Bird	Indeterminable bird
	Snake	Indeterminable snake
	Unknown	Indeterminable zoomorphic figure
	Anthropomorph	Indeterminable or male anthropomorphic figure
	SFF	Schematic Female Figure
	Vulva	Vulva
	Point(s)	Simple point or series of points
	Sign	Complex sign (rectangular shape, meander shape, etc.)
	Paired strokes	A series of paired strokes
	Arrow	An arrow
Underlying surface (Surface)	Clay	The support is formed by clay, which can be in primary origin, formed by weathering of an underlying lithology, or in a secondary position, formed by sedimentation.
	Limestone	The surface consists of limestone, of different petrographic composition. In the case of Altxerri, there are also calcarenite and marl surfaces. It may be occasionally mixed with other lithologies (e.g., speleothems) but limestone comprises the largest part.
	Speleothem	A calcium carbonate precipitate that has formed on another surface. It usually appears in the form of calcite or aragonite crystals.
Surface texture (Texture)	Hard	The surface is hard and difficult to engrave with a lithic instrument
	Soft	The surface allows easy engraving with a lithic instrument, although it is difficult to engrave with fingers.
	Very Soft	The surface allows easy engraving with fingers.
Format	Complete	The figure appears complete, or at least 3/4 parts of the body have been represented.
	Headless	The figure has been represented without a head.
	Protome	The figure represents the head with or without the chest and frontal leg of the animal.
	Back	The figure has been represented without the front half body.
	Isolated Part	Only a portion of the figure has been represented (e.g., a leg, the horns, etc.).
	N.F.	This is not a figurative representation (it is an abstract sign).
Finishing grade (Finish.)	Simple	The figure has been made in a few strokes and quickly, without details and without being finished (the strokes do not complete the figure).
	Finished	The figure is finished (almost the entire outline is represented), although it does not present details.
	Detailed	The figure presents between one or two details (eye, ear, fur, etc.).
	Very Detailed	The figure has more than two combined details (for example, the eye, the scapular stain, and the “M” shape of fur in the belly have been represented).
	N.F.	This is not a figurative representation (it is an abstract sign).

**Table 2** (continued)

Variable	Values	Meaning
Orientation (Orient.)	Right	The figure's body (or head) points to its right.
	Left	The figure's body (or head) points to its left.
	N.F.	This is not a figurative representation (it is an abstract sign).
Inclination (Incl.)	Horizontal	The body of the figure is arranged parallel to the cave floor
	Inclined	The body of the figure is arranged diagonally to the cave floor
	Vertical	The body of the figure is arranged orthogonally to the cave floor
	Inverted	The body of the figure is arranged parallel to the cave floor, but the legs point upwards.
	N.F.	This is not a figurative representation (it is an abstract sign).
Use of Morphologies (morph.)	Use of morphologies	The figure takes advantage of the shapes of the surface to highlight or represent some part.
	No use	The figure does not use the morphologies of the cave.
Bounded canvas (bounded.)	Bounded canvas	The figure or the figures are bounded by a particular morphology of the surface (for example fissures surrounding a figure, or a figure arranged inside a hole).
	Not bounded	The figure is not arranged in any particular shape of the cave.
Length	(Numerical)	Maximum length of the figure (in cm).
Height	(Numerical)	Maximum height of the figure (in cm).
Dimension (Dim.)	(Numerical)	Maximum dimensions of the figure (in cm <sup>2</sup> ).

## Multivariate statistical analysis

The results obtained in the previous step were statistically processed using the *R* 4.2.3 console through *Rstudio* 2023.06.2. The Factor Analysis for Mixed Data (FAMD) was employed to simultaneously analyse the information from numeric and qualitative variables (Pages 2004). Given the relatively large sample size (500 individuals), it might have been possible to resort to Multiple Correspondence Analysis (Pagès 2002) by grouping these values into thresholds. However, this method was chosen since the numeric variables (6) accounted for 35.29% of the variables to be analysed. Subsequently, the data were regrouped by Hierarchical Clustering on Principal Components (HCPC) with a 95% confidence interval (Husson et al. 2010). In addition to these multivariate analyses, other descriptive analyses were conducted to visualize the obtained values for spatial variables in each cave and in the clusters discriminated through the FAMD and HCPC analyses. The packages used, as well as the codes employed in the console, can be consulted on <https://github.com/inakiintxaurbe/spatial-organization-patterns-related-to-magdalenian-cave-art>.

## Results: from individuals to the groups

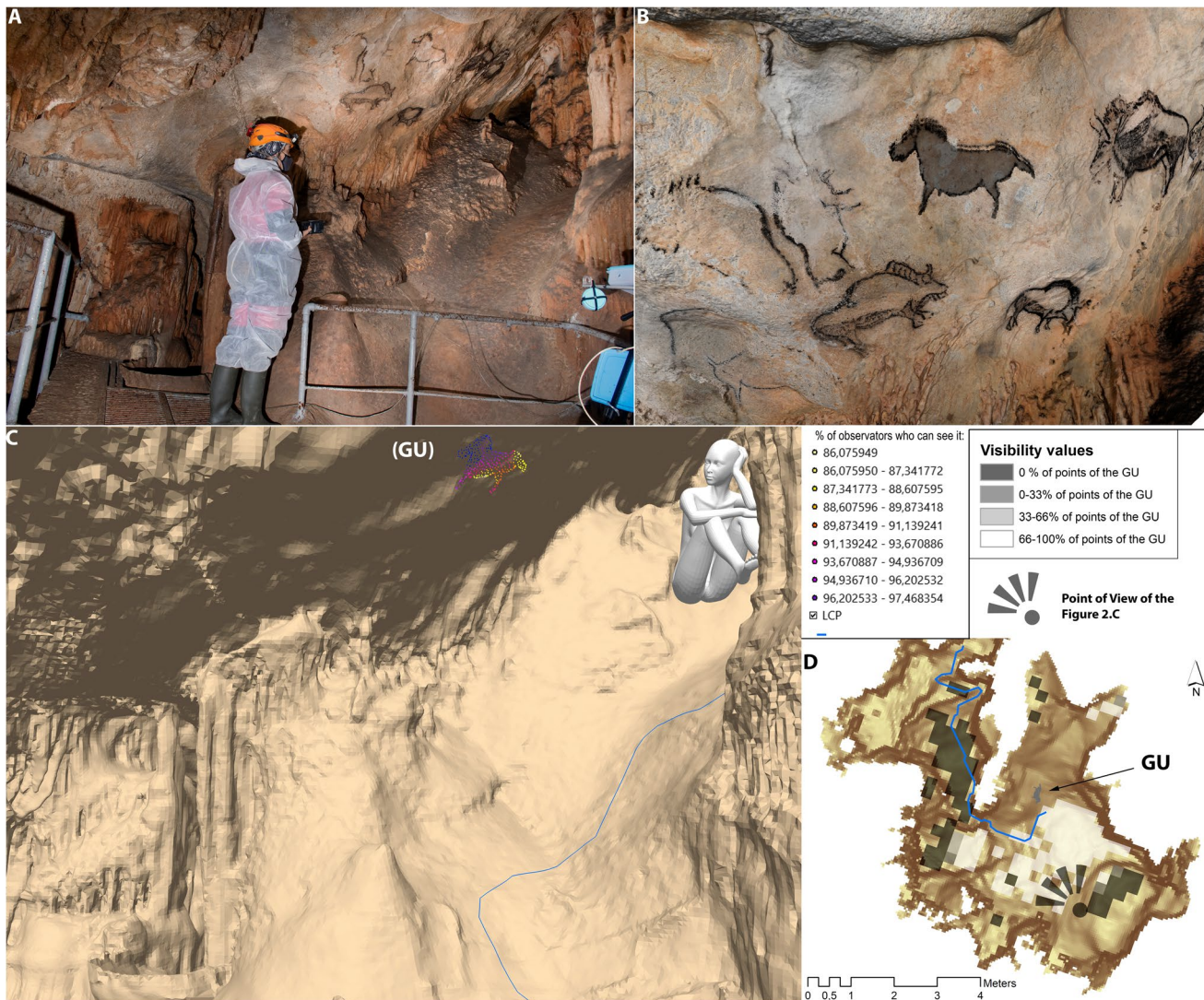
### 1st FAMD and HCPC analysis

The spatial and iconographic dataset of each of the 500 analysed Graphic Units (GUs) underwent an initial statistical analysis with Factor Analysis for Mixed Data (FAMD), where the dimensions explained 6.3% and 3.8% of the

variance. Subsequent clustering through Hierarchical Clustering on Principal Components (HCPC) discriminated four main clusters within the 95% confidence interval, briefly described below (Fig. 3). A more detailed explanation of variable weights in the main dimensions and other statistical analysis aspects, along with an extended description of clusters, can be found in Supplementary Materials Sect. 6. A summary of each cluster's characteristics is available in Table 4. The four discriminated clusters in the analyses are described as follows:

The first cluster consists of 287 individuals, accounting for 57.4% of the analysed sample. Regarding qualitative variables, the group is characterized by figures with a complete format (70% of individuals with this feature belong to this cluster) and a very detailed or detailed finishing (82.86% and 75.9% of individuals with these characteristics belong to this cluster, respectively). As for the theme, the cluster is primarily composed of bison (40.2% of all bison belong to this cluster). Techniques vary, but the use of black paint is characteristic (87.89% of individuals with this feature belong to this cluster), and the combination of techniques is also frequent. Concerning numeric variables, the distance to the ground (with an average of 1.35 m from the ground) and the number of potential observers (an average of 7.4) positively influence the group, while variables related to difficulty of access (average = 96.57), length of the optimal access route (average = 98.86 m), and estimated arrival time (average = 4.51 min) exert a negative influence. In summary, the group is characterized by highly crafted figures (complete, detailed, and created with combined techniques) arranged on relatively high surfaces, with moderate difficulty of access and not very significant distance from the entrance. The use





**Fig. 2** Example of the workflow followed for the extraction of georeferenced geometric information for each GU, in this case for the horse D.III.06 from Santimamiñe. **(A)** The geometry of the cave in its current state, as well as that of the rock art, is documented using the TLS and photogrammetry, respectively. **(B)** A restitution of the original state of the panel is carried out by modifying its texture and geometry (to the extent possible). The process involves georeferencing using common targets with the point cloud scanned with TLS (Terrestrial Laser Scanning) and georeferenced with GNSS (Global Navigation Satellite System). The georeferencing is performed in *Photoscan*™ 1.2.0.2152 from *Agisoft*®. Subsequently, through *MeshLab* 2022.2, using the “Select by colour” tool, we chose black (the GU of interest).

Subsequently, we selected the rest of the panel using “Inverse selection.” **(C)** Once the GU (Graphic Unit) model is separated, and after obtaining the reconstructed virtual original geometry of the cave (see Intxaurre et al. 2023), both models are analysed in ArcGIS®, using the workflow summarized in the script (<https://github.com/inakiintxaurre/spatial-organization-patterns-related-to-magdalenian-cave-art>). By analysing the vertices of the geometry occupied by the GU, we can observe which parts of the figure are more visible, as well as other data such as the optimal access route. **(D)** The data can be visualized in *ArcScene*™ (3D GIS) or *ArcMap*™ (2.5D GIS with orthogonal view)

of morphologies to enhance the figures is also characteristic in this group of GUs (Table 4). These figures are described as possessing features that favour their visibility, location, and understanding by the group (González Sainz 2005).

The second cluster consists of 146 individuals, representing 29.2% of the analysed sample. Regarding qualitative variables, the group is characterized by figures with a simple finish (58.9% of individuals in this cluster display

this feature), incomplete format (headless figures or isolated parts represent 56.06% and 56.25% of individuals belonging to this cluster, respectively), and a rather heterogeneous theme, although with a strong emphasis on ibex and figures difficult to determine (70.59% and 60% of individuals with these characteristics belong to this cluster, respectively). Techniques vary, but simple engraving is common, sometimes combined with multiple engraving



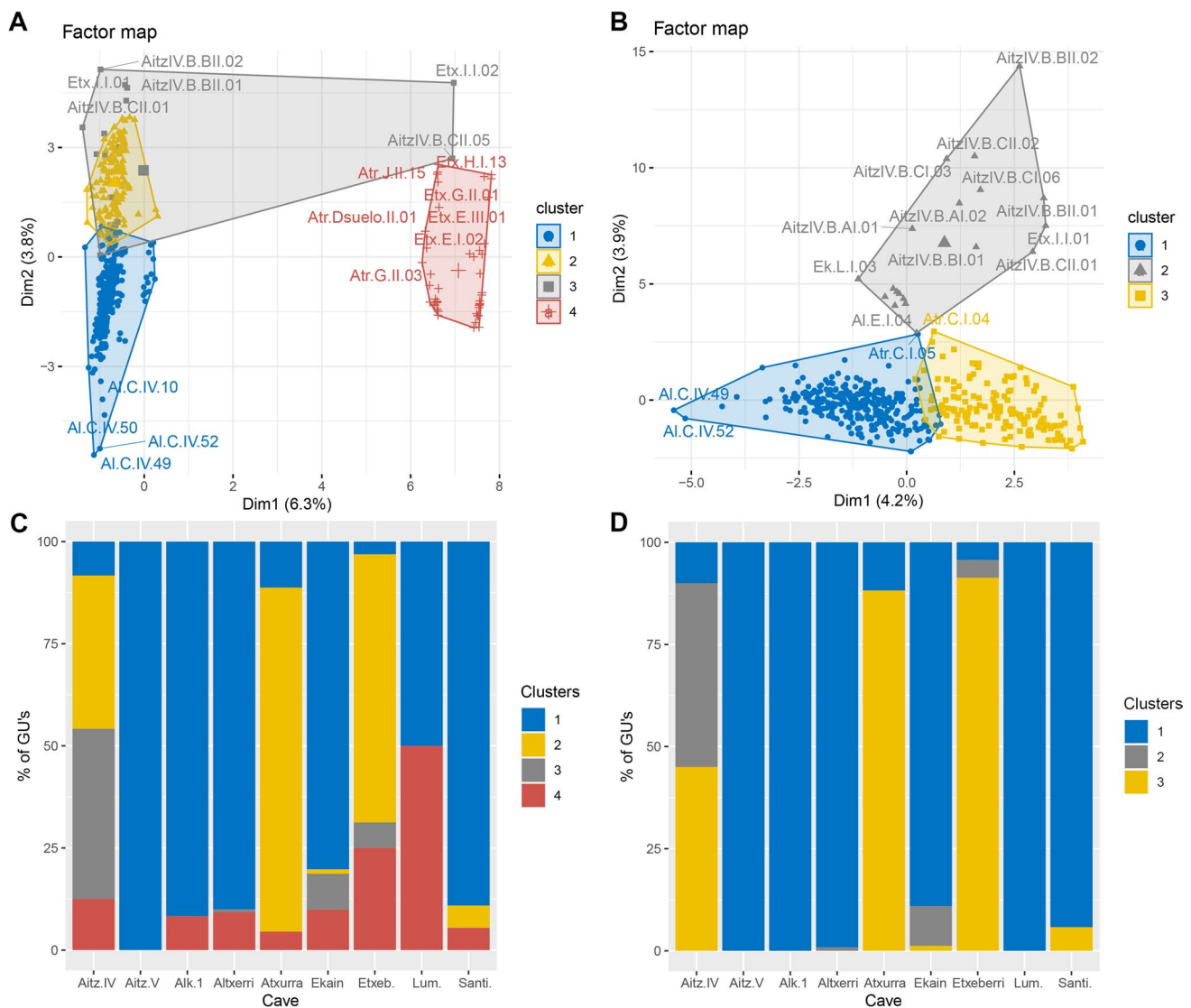
**Table 3** Table of the analysed spatial variables for each Graphic Unit (GU). \* The estimations of the posture of the artist are based on the information of the variable “Distance to the ground”, and the criteria applied by B. Ochoa and M. García-Díez 2018

Variable	Values	Meaning
Difficulty value of access (DV)	(Numerical)	Accumulated access difficulty value that measures the cost of transiting each space in the cave, estimated from the archaeological experiments presented in a previous study (Intxaurbe et al. 2021). The value is given in 1/(m/s).
Least cost path length (LCP)	(Numerical)	This variable estimates the length of the optimal route that has been obtained from the calculation of the costs of crossing a cave (Intxaurbe et al. 2021). The value is given in metres and considers the three-dimensional topographic length of the path (that is, it also considers the slopes).
Estimated time of arrival (ETA)	(Numerical)	The variable estimates a minimum arrival time to the sector, in minutes (Intxaurbe et al. 2021).
Distance to the ground (Dist. Gr.)	(Numerical)	The software estimates a centroid for the figure and calculates the nearest artist-usable position. This will have a slope of less than 30°. Subsequently, it will measure the distance between two points, the result will be given in metres, considering whether it is positive (the artist is below the figure) or negative (the artist is in a higher position).
Posture*	Crouching/Kneeling/Sitting/Lying down	$0 \leq \text{Distance to the ground} < 1$
	Leaning	$1 < \text{Distance to the ground} \leq 1.3$
	Leaning/Upright	$1.3 < \text{Distance to the ground} \leq 1.7$
	Upright	$1.7 < \text{Distance to the ground} \leq 1.8$
	Elevated	$1.8 > \text{Distance to the ground}$
Viewers upright	(Numerical)	The software estimates the maximum number of potential viewers who are upright, in areas with a height greater than 1.599 m (Holt 2003; Intxaurbe et al. 2022). To do this, it uses previous estimations (Neufert 1951; Pastoors and Weniger 2011) that indicate that a standing person occupies an area of 0.77 m <sup>2</sup> .
Seated viewers	(Numerical)	The software estimates the maximum number of potential viewers who are seated, in areas with a height between 0.71 and 1.599 m (Intxaurbe et al. 2022). To do this, it uses previous estimations (Ruiz-Redondo 2014) that indicate that a person sitting down occupies an area of 0.90 m <sup>2</sup> .
Viewers lying down	(Numerical)	The software estimates the maximum number of potential viewers who are lying down, in areas with a height between 0.24 and 0.71 m (Intxaurbe et al. 2022). To do this, it uses previous estimations (Neufert 1951; Pastoors and Weniger 2011) that indicate that a person lying down occupies an area of 1.75 m <sup>2</sup> .
Total viewers (View.)	(Numerical)	The software estimates the maximum size of a potential audience.

(64.44% and 45.92% of individuals with these characteristics belong to this cluster, respectively). Concerning numeric variables, the number of potential observers (with an average of 5.8) and the distance to the ground (with an average of 0.99 m from the ground) have a negative influence on the group, while variables related to the difficulty access value (average = 382.56), the length of the optimal route (average = 280.49 m), and the estimated arrival time (average = 25.93 min) have a positive quantile weight in the normal distribution. In summary, the group is characterized by schematic or very simple and quickly resolved figures (incomplete, small, and created with a single technique) in low panels, but with a notable distance from the entrance. These figures are described as having characteristics that do not favour their visibility, location, and understanding by the group.

The third cluster consists of 21 individuals, accounting for 4.2% of the analysed sample. Regarding qualitative

variables, the group is characterized by figures made on clay (100% of individuals with this feature belong to this cluster) or very soft-textured supports (72.22% of individuals with this feature belong to this cluster). The use of certain techniques such as modelling and finger engraving is exclusive to this group. Concerning the theme, it is quite heterogeneous, although horses are abundant (42.86% of the GUs in this cluster represent equids), and vulvas are exclusive to this group. Regarding numeric variables, the dimensions of the figures (with an average of 2946.95 cm<sup>2</sup>) and the difficulty of access (with an average of 425.03) are determinative in this group. In other words, the group is characterized by figures modelled or finger-engraved on clay or very soft surfaces, such as weathered limestone. Additionally, these figures are very difficult to access and are relatively large compared to other groups, as noted by other authors in comparable cases (González Sainz 2019/20). In summary, these figures utilize soft surfaces like clay or weathered calcite, a



**Fig. 3** (A) Factorial map extracted from the FAMD of the first analysis, discriminating the four groups through the HCPC. (B) Factorial map extracted from the FAMD of the second analysis (excluding non-figurative representations), discriminating three groups through the

HCPC. (C) Percentage of GUs belonging to each cluster in the caves studied in the first analysis. (D) Percentage of GUs belonging to each cluster in the caves studied in the second analysis

particular characteristic (though not exclusive) of Magdalenian art around the Bay of Biscay (Ochoa et al. 2018; Garate et al. 2020d).

The fourth cluster is composed of 46 individuals, representing 9.2% of the analysed sample. In terms of qualitative variables, the group is characterized almost exclusively by non-figurative formats, except for the paired strokes Etx.I.I.02 and the points AitzIV.B.CII.05, which are included in Cluster 3 because they are made on clay. The theme of signs, points, and projectiles is exclusive to this group, and the technique is heterogeneous, with a notable presence of red paint, as 57.14% of the analysed

sample with this characteristic belongs to this group. This has been noted by other authors for a Magdalenian chronology (Rouzaud 1978; Vialou 1986; Ruiz Redondo 2016; Clottes 2018), making it relevant, especially considering that we have not included graphic elements such as indistinct spots and possible traces produced by non-voluntary abrasions (Medina-Alcaide et al. 2018) in this study. Regarding numerical variables, the size of the figures (with an average of 460.96 cm<sup>2</sup>) would exert a negative quantile weight on the normal distribution. In summary, the group is characterized by ideomorphic or abstract representations of relatively small size.

**Table 4** Description of each cluster with the most determining variables and categories in each one. In the case of numerical variables, the average value for each one has been shown. \* The v-test here corresponds to the quantile of the normal distribution which is associated with p-value. A v-test value greater than 1.96 corresponds to a

p-value less than 0.05 (i.e., all categories are significant); if the v-test is positive, it means that the category is over-expressed for the category and if the v-test is negative it means that the category is under-expressed. The acronyms of the variables can be viewed in Tables 2 and 3

Variables	Cluster 1	Cluster 2	Cluster 3	Cluster 4
Theme	Bison (v-test: 7.03)	Ibex (v-test: 6.44)	Vulva (v-test: 3.14)	Point(s) (v-test: 10.24)
Tech.	Black P. (v-test: 8.6)	Simple Engr. (v-test: 7.72)	Finger Engr. (v-test: 9.74)	Red P. (v-test: 8.48)
Surface	Clay (v-test: -5.59)	Clay (v-test: -3.34)	Clay (v-test: 12.31)	-
Texture	Very Soft (v-test: -4.04)	Hard (v-test: 2.87)	Very Soft (v-test: 8.31)	-
Format	Complete (v-test: 5.49)	Headless (v-test: 4.89)	Headless (v-test: -1.98)	N.F. (v-test: 16.78)
Finish	Very detailed (v-test: 4.81)	Simple (v-test: 5.73)	-	N.F. (v-test: 16.78)
Orient.	Left (v-test: 3.19)	N.F. (v-test: -5.59)	-	N.F. (v-test: 16.78)
Incl.	Vertical (v-test: 4.41)	Horizontal (v-test: 6.61)	Horizontal (v-test: 2.51)	N.F. (v-test: 16.78)
Morph.	Use (v-test: 2.31)	-	-	No use (v-test: 2.07)
Bounded	Bounded (v-test: 2.39)	No bounded (v-test: 2.28)	-	-
Dim.	-	-	2946.95 (v-test: 3.84)	460.96 (v-test: -3.43)
DV	96.57 (v-test: -11.05)	382.56 (v-test: 9.32)	425.03 (v-test: 3.79)	-
LCP	98.86 (v-test: -15.09)	280.49 (v-test: 17.39)	-	-
ETA	4.51 (v-test: -15.06)	25.93 (v-test: 16.8)	-	-
Dist. Gr.	1.35 (v-test: 6.29)	0.99 (v-test: -6.7)	-	-
View.	7.4 (v-test: 3.34)	5.8 (v-test: -2.71)	-	-

## Second FAMD and HCPC analysis

As non-figurative representations, even excluding fortuitous and unintentional ones, are challenging to characterize (Sauvet et al. 1977), we repeated the combined FAMD and HCPC analysis, excluding the fourth cluster, as well as the elements Etx.I.I.02 and AitzIV.B.CII.05 from the third cluster, since they represent abstract or non-figurative representations. This second analysis, with 452 individuals, where

the first two dimensions explained 4.2% and 3.9% of the variance (Fig. 3), discriminated three groups almost identical to the first three groups of the previous analysis.

The first cluster of this second analysis is identical to the first cluster of the first analysis, although the v-tests of the same are slightly modified (Table 5). The second cluster of the second analysis, on the contrary, is similar to the third cluster of the first analysis but excluding the two non-figurative motifs mentioned above. Finally, the third group

**Table 5** Description of each cluster in the second analysis with the most determining variables and categories in each one. In the case of numerical variables, the average value for each one has been shown. \* The v-test here corresponds to the quantile of the normal distribution which is associated with p-value. A v-test value greater than 1.96 corresponds to a p-value less than 0.05 (i.e., all categories are significant); if the v-test is positive, it means that the category is over-expressed for the category and if the v-test is negative it means that the category is under-expressed. The acronyms of the variables can be viewed in Tables 2 and 3

Variables	Cluster 1	Cluster 2	Cluster 3
Theme	Bison (v-test: 5.02)	Vulva (v-test: 3.14)	Ibex (v-test: 5.92)
Tech.	Black P. (v-test: 7.76)	Finger Engr. (v-test: 8.94)	Simple Engr. (v-test: 8.42)
Surface	Limestone (v-test: 2.43)	Clay (v-test: 11.63)	Clay (v-test: -3.37)
Texture	Very Soft (v-test: -4.17)	Very Soft (v-test: 7.46)	Hard (v-test: 2.92)
Format	Complete (v-test: 3.04)	Protome (v-test: 1.97)	Headless (v-test: 4.29)
Finish	Very detailed (v-test: 3.79)	-	Simple (v-test: 4.58)
Orient.	-	-	-
Incl.	Vertical (v-test: 4.25)	Horizontal (v-test: 3.05)	Horizontal (v-test: 4.72)
Morph.	-	-	-
Bounded	Bounded (v-test: 2.18)	-	No Bounded (v-test: 2.54)
Dim.	1285.56 (v-test: -2.91)	3240.84 (v-test: 4.21)	-
DV	96.57 (v-test: -11.83)	377.51 (v-test: 3.19)	382.56 (v-test: 10.81)
LCP	98.86 (v-test: -16.63)	-	280.49 (v-test: 17.27)
ETA	4.51 (v-test: -16.31)	-	25.93 (v-test: 17.01)
Dist. Gr.	1.35 (v-test: 6.55)	-	0.99 (v-test: -6.77)
View.	7.4 (v-test: 3.32)	-	5.8 (v-test: -2.89)



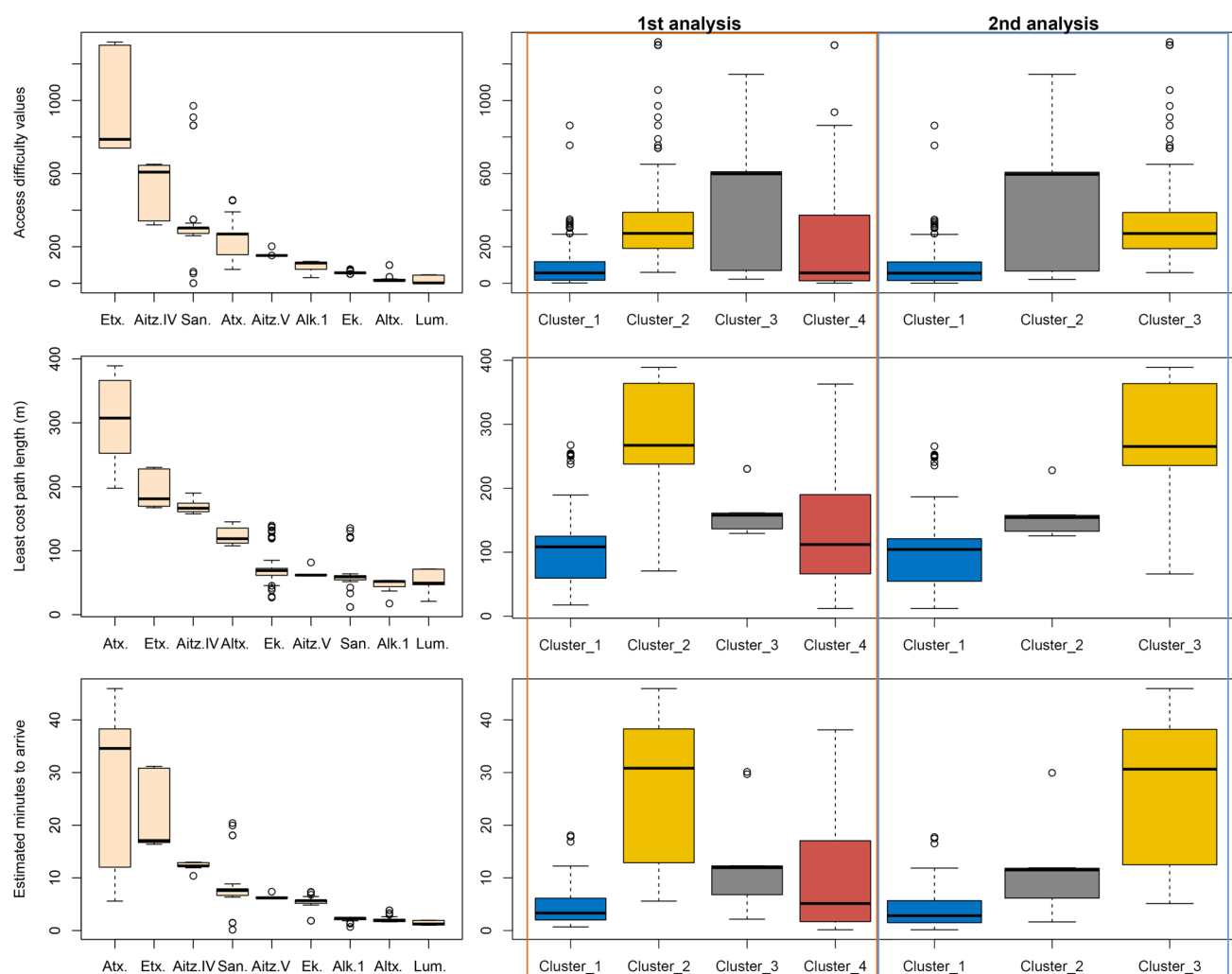
would be identical to the second group described in the first analysis.

### Visualization of the data of the spatial variables in each cave and in each cluster described in the preceding analyses

Finally, since spatial variables have a higher quantile weight in the normal distribution (Table 5), compared to iconographic variables, we conducted a visualization of the spatial analyses in each cave and in each cluster described in the preceding analyses. In this way, we were able to observe that almost all caves exhibit a similar cluster proportion, except in the case of Atxurra, Etxeberri, and Aitzbitarte IV (Fig. 3). It should be highlighted that these are the caves with the highest values of accessibility difficulty, especially the

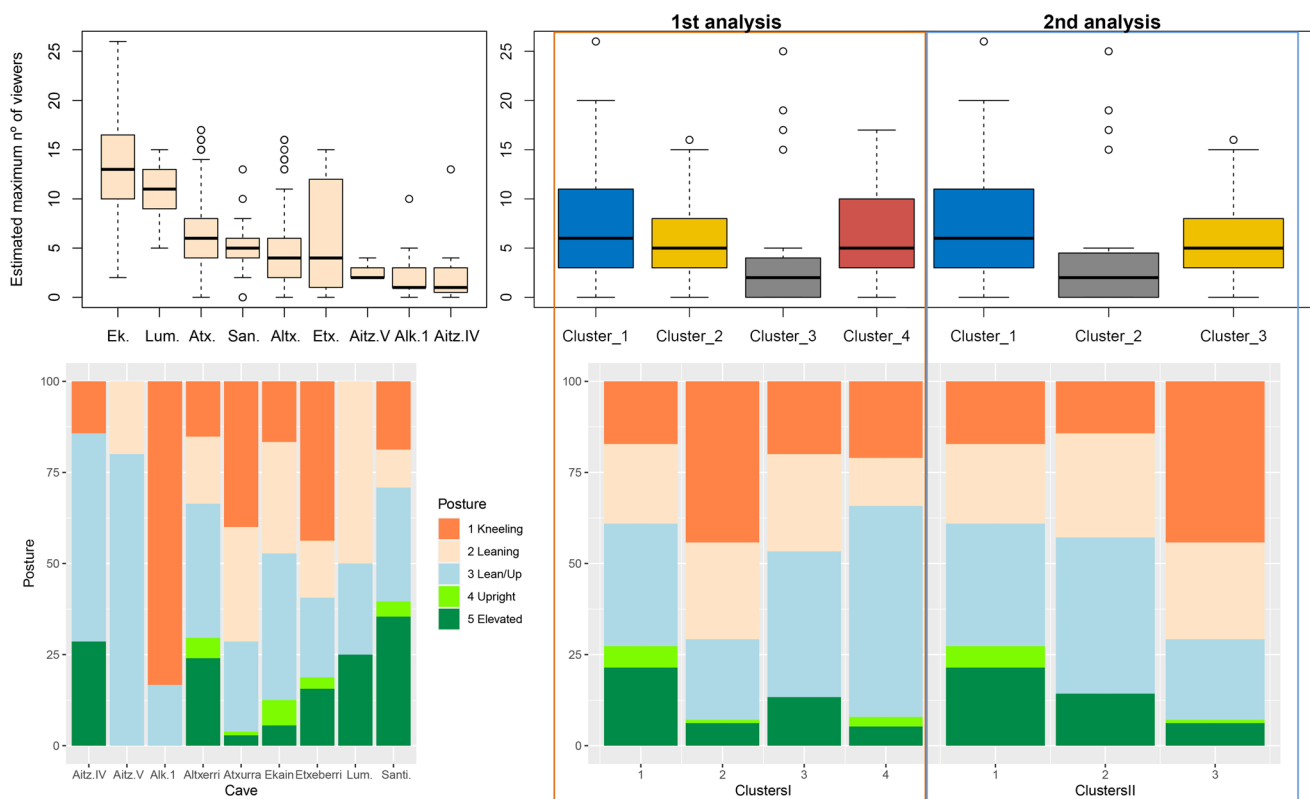
figures located near the “Puits de l’Ange” (Sectors H, I, and J) in Etxeberriko Karbia, an immense 16-metre precipice where the highest values have been recorded (Fig. 4).

In contrast, the results of the visibility analyses (Fig. 5) were unevenly distributed in the caves. Three of the sites (Aitzbitarte IV, V, and Alkerdi 1) obtained low values (estimates of fewer than three potential observers for each GU), four (Etxeberri, Altxerri, Santimamiñe, and Atxurra) obtained somewhat higher values, with an average close to five observers for each GU, and two of the caves (Ekain and Lumentxa) would have very high visibility values (estimated averages of more than 10 potential observers) for the GUs. Finally, if we analyse the distance to the ground of the figures and estimate the posture of the artists based on that data, the results are also unevenly distributed, both in the caves and in the clusters. For example, postures close to



**Fig. 4** Statistics (minimum, first quartile, median, mean, third quartile and maximum) of the obtained values for each of three spatial variables (Access difficulty values, Least cost path length and Estimated minutes to arrive) according to the cave studied, and the clusters of

GUs determined in the first and second analysis. The R code used, as well as the packages, is accessible through <https://github.com/inaki-intxaurre/spatial-organization-patterns-related-to-magdalenian-cave-art>



**Fig. 5** Statistics (minimum, first quartile, median, mean, third quartile and maximum) of the obtained values for the Estimated maximum number of viewers according to the cave studied, and the clusters of GUs determined in the first and second analyses. Estimated posture for the artist, according to the distance between the optimal place of execution and the figure, for each one of the studied caves, and the

clusters of GUs determined in the first and second analysis. Areas of the caves in which the morphologies of the passages influenced the estimated position of the artists were excluded (i.e., areas with low ceilings) before the analysis. The R code used, as well as the packages, is accessible through <https://github.com/inakiintxaurre/spatial-organization-patterns-related-to-magdalenian-cave-art>

the ground were strongly associated with certain caves (for example, Alkerdi 1 and Etxeberri), as well as the second cluster of the first analysis, or its counterpart, the third of the second analysis, which would encompass figures with characteristics that hinder their visibility. This particularity appeared interesting, so to rule out cases where the morphology of the cave forced a specific posture (i.e., places with low ceilings), we repeated the analysis, observing that this association between these postures and certain caves and/or clusters continued to be repeated (Fig. 5).

## Discussion: identifying possible spatial patterns for Magdalenian cave art

As explained above, despite conducting two consecutive FAMD and HCPC analyses, practically identical clusters have been discriminated. This is even more striking when considering that in both analyses, the quantile weight in the normal distribution of variables related to the spatial context had a greater impact. In other words, factors related to the

arrangement of figures in the caves were decisive in defining clusters in both analyses.

In simpler terms, the results presented earlier support the existence of two almost antagonistic groups composed of figures with characteristics that either favour or hinder their visibility. This is due to a combination of factors related to the cave morphology (difficulty of placement, locations that favour or hinder visibility, etc.) and factors specific to the studied GUs (use of one or multiple techniques that either favour or hinder visibility, level of detail that facilitates or hinders understanding, etc.). In fact, the number of potential observers (i.e., the visibility of the figures) is higher in clusters with variables that promote the visibility and understanding of the figures, while the cluster of “hidden and/or simple” figures exhibits the opposite trend (Fig. 5).

Additionally, there are also two groups of figures that have been differentiated by technique and type of support (Cluster 3 in the first analysis and 2 in the second analysis) and by variables related to the theme (Cluster 4, only in the first analysis). Cluster 3 in the first analysis (and 2 in the second) is related to representations made on very soft surfaces

such as clay, which are mainly created using fingers and sometimes include modelling of the figures to enhance their volume as bas-reliefs or sculptures. These types of representations are closely linked to the context of deep caves, especially in areas with high difficulty of access values (Fig. 4). Additionally, this does not seem to be a pattern limited only to our study region. Caves like El Castillo (Groenen et al. 2012) (Fig. 6), La Garma (Alerta 2021; Balbona 2021) (Fig. 6), Bèdeilhac, Ker-de-Massat, or Niaux (Vialou 1986) present animal figures engraved in the clay pavement of terminal sectors or areas with very difficult access, similar to the horse Etx.I.I.01 in the Etzeberri cave (Fig. 6).

Similarly, caves such as Covaciella (García Díez et al. 2016), Hornos de la Peña, Oxocelhaya, Erberua, Tuc d'Audoubert, or Combarelles III (Cleyet-Merle et al. 2016) feature figures engraved on soft surfaces of the walls of the terminal sectors, as seen in Ekain Cave. Finally, modelled figures and sculptures in clay are almost exclusive to these terminal and/or very difficult-to-access areas, such as the chimney models of Aitzbitarte IV (Fig. 4), as seen in Tuc d'Audoubert, Labouiche (Meroc 1959), Montespan (Rivenq 1984), Labastide (Simonnet et al. 1984), and Erberua. This type of representation may tend to be found in areas that are so difficult to access due to their fragility (Rouzaud 1978; Garate et al. 2020d), as it is unlikely that they would preserve in other more accessible and therefore more visited areas. However, it cannot be ruled out that

there are other symbolic or cultural reasons. In fact, the repetition of this pattern in caves that were sealed at the end of the Last Glacial Period and present exceptional preservation conditions, as in Erberua, Fontanet (Clottes et al. 1984), or La Garma, seems relevant in this regard. Another determinative characteristic of this cluster is the exclusive association of the vulva theme with soft or clayey supports. This is repeated in other Magdalenian caves in the region (Oxocelhaya) and more distant ones (e.g., Bèdeilhac).

Cluster 4 is composed of non-figurative representations. Regarding this, it is noteworthy that this study has not included any site presenting series of complex conventional or standardized signs. In fact, such complex signs are not common in the study region (around the central Bay of Biscay). We can only mention Armintxe Cave (González Sainz 2019/20) or Erberua (Larribau 2013) as two exceptional cases containing this type of ideomorph—in this case, series of P-shaped claviforms similar to those found in caves on the northern slope of the Pyrenees, such as Tuc d'Audoubert (Bégouën et al. 2009), or Trois-Frères (Bégouën et al. 2014). However, these cases have not been analysed here due to a lack of three-dimensional facsimiles and geomorphological studies that would help understand the state of both caves at the time they were decorated. Therefore, conclusive data relating Magdalenian abstract graphemes to specific spatial parameters cannot be extracted at the moment. Still, there

**Fig. 6** Magdalenian horse figures engraved on soft materials in the floor of various caves. In all cases, these are areas that are very deep and difficult to access. (A) Horse Etx.I.I.01 in Etzeberri Karbia (D. Garate), accessible after crossing several vertical parts (including an exposed passage over a 16-metre abyss). (B) La Garma, a horse engraved in the floor of a new elevated gallery discovered in 2020 (P. Arias & R. Ontañón), accessible after climbing two vertical and exposed parts. In this case, it is difficult to assert with certainty whether the artists entered from the current access point or some other blocked entrance. In any case, it is suggestive that there are extensive Magdalenian occupation areas in the first scenario. (C) El Castillo, an engraved horse in the Sector “Tréfonds” (S. Salazar & O. Spaey), in the deepest part of the cave, accessible after crossing several vertical obstacles





are precedents for interesting studies in this direction (Robert 2017; Recht 2020).

The presence of certain types of figures according to their location in the cave (e.g., Groenen and Groenen 2019), and the existence of different types of representations in terms of their functionality, has already been noted by other authors (e.g., Leroi-Gourhan 1958; González García 2001; González-Sainz 2005, 2017). For instance, Laming-Emperaire (1962) pointed out the existence of two types of panels, “*les uns destinés à être vus et sans doute admirés par une assistance, les autres soigneusement cachés*” (some destined to be seen and undoubtedly admired by an audience, the others carefully hidden). On the other hand, the specific theme of the “visible” clusters (the first cluster of the first analysis includes 87.79% of the analysed bison), confirms the idea proposed by the authors mentioned earlier, who indicated that “central panels” mainly consisted of bison (in addition to horses, aurochs, and mammoths). González-Sainz (2005, 2017) also emphasizes the greater visibility and hosting capacity of these “main” sectors, a characteristic that is also reflected in the two analyses we have conducted (Fig. 5). Additionally, terminal spaces or those with very complicated access mostly display GUs from the “hidden” clusters (Figs. 4 and 5). It is also intriguing to observe how the use of surface morphologies (shapes that complete the representations, accidents that frame them, etc.) is characteristic of the clusters of “visible” figures in both analyses (Tables 4 and 5). Some authors have debated whether the existence of certain cave forms could have had some effect on the thematic selection of Palaeolithic artists (Sauvet and Tosello 1998; Sakamoto et al. 2020; Wisher et al. 2023b; Hodgson 2023). To these hypotheses, we add the possibility that the existence of these forms could have been determining factors when choosing a particular space for the transmission of a shared graphic code. Finally, our work has focused on individual entities, not collective ones (sectors or panels), and this analytical criterion allows us to see that belonging to a cluster is not exclusive to a specific type of sector. That is, it is possible to find figures from a specific cluster (associated more with high difficulty values, lower finishing degree, etc.) in panels with a majority presence of the opposing cluster. This underscores the inherent complexity of compositions and the hierarchy of transmission graphic codes. In other words, the results imply the existence of a multifunctional graphic communication system in the case of Magdalenian cave art created inside caves.

If we analyse the estimates of spatial variables (accessibility, visibility, etc.) for each set, we have observed that the results are distributed unevenly. That is, there are caves that predominantly contain figures with characteristics that enhance their visibility, while in others, the opposite is true. Certain authors have argued for the existence of aggregation sites (Conkey et al. 1980) and initiation sites (sometimes

within the same cave) (Lorblanchet 1995; Utrilla and Bea 2008). The former could be places or centres of ritual activities (Dolukhanov 1997) capable of bringing together many people at once, while the latter would be more secluded areas of the caves, hidden and difficult to access, visited very occasionally (Sieveking 1997). To illustrate these hypotheses, the information provided by well-preserved caves mentioned earlier (La Garma, Erberua, Tuc d'Audoubert, or Fontanet) suggests that areas near the entrances (including some with rather difficult access) were intensively frequented (Clottes et al. 1984; Arias 2009), while other deeper areas were visited very occasionally (Bégouën et al. 2012).

Based on the results of the statistical analysis, Ekain and Lumentxa could be two caves that acted as aggregation sites, as proposed by Utrilla (1994), since they are the sites that show the highest values for parameters favouring their visibility and the estimated potential number of observers. This is especially notable for the former, given the high number of figurative representations it contains and the technical complexity of these (Fig. 7). In contrast, other sites, such as Santimamiñe (Utrilla 1994), may have a somewhat lower hosting capacity, with averages close to five people in the same place, at least in decorated sectors, and perhaps could be interpreted as “concentration places”. In the case of Altxerri, Utrilla (1994) argued that it was a sanctuary of lesser importance, in this case, considering its small and difficult-to-access entrance. Our results give it an average visibility similar to Santimamiñe, although it predominantly features graphemes from the “visible” cluster, with some areas paradigmatic in terms of their high visibility from the main transit axis, as pointed out by other recent research (Ruiz-Redondo 2014; Intxaurbe et al. 2022). Aitzbitarte IV, despite its immense size and hosting capacity (Utrilla 1994), falls outside the group of caves with great hosting capacity, as the decorated sectors are in very difficult-to-access places with less hosting capacity. In any case, it is important to note that this may be due to a taphonomic factor, as the cave underwent graffiti removal in 1999, with the almost certain loss of rock art that could have been preserved underneath, as the only preserved traces in the main gallery are located in places that were not cleaned (Garate et al. 2013b). Aitzbitarte V and Alkerdi 1 would be two other caves with little hosting capacity, as indicated by other recent studies (Garate and Rivero 2015; Garate et al. 2016a).

Finally, sites like Atxurra, and especially Etxeberri, have areas with a high hosting capacity (“Repisa de los Caballos” or Sector J in the first and “Salle des Peintures” or Sector E in the second) that contrast with other sectors in the same cave (much narrower and secluded), as well as their high access difficulty values (Fig. 7). Additionally, as previously indicated, the graphic units (GUs) in these assemblages are almost exclusively associated with clusters of figures that exhibit characteristics hindering their visibility

**Fig. 7** Two antagonistic examples of decorated main sectors, created with *Blender 3.3.0* using georeferenced models of the panels and cave geometry: (A) “Zaldei” (Ekain, Sector E) and (B) “Salle des Peintures” (Etxeberri, Sector E). Although both are located in deep areas of the endokarst (in total darkness), in the first one, accessibility, visibility, and hosting capacity favour their visualization, while in the second one, spatial parameters cause the opposite. Additionally, although both cases involve a combination of techniques (both cases feature polychrome paintings), the figures are more easily recognizable in the first example. Finally, our work has focused on individual entities, not collectives (sectors or panels), and this analytical criterion allows us to see that belonging to a cluster is not exclusive to a specific type of sector. That is, the panels in Image A contain figures from the hidden cluster, and those in B contain figures from the visible cluster. However, in the first example, “visible” figures are the majority, while in the second, “hidden” figures predominate. The digital model represents the average height for female individuals during the Late Upper Palaeolithic (154.5 m), according to Holt 2003; and Cox et al. 2019



and understanding by the group, suggesting that these caves might have served other functions related to socio-cultural activities such as rites of passage (Owens and Hayden 1997). Another noteworthy aspect of the figures in the “hidden” clusters is that they were mostly created in positions close to the ground (Fig. 7). This detail becomes even more relevant when considering that, after eliminating areas where the morphology forced constrained postures (i.e., crawlways and passages), the results still show a preference for lower panels (Fig. 5). Without excluding other explanations, such as the intention to use more discreet spaces, this peculiarity could indicate the presence of artists of small stature (Bahn 2015; Fernández-Navarro et al. 2022). The existence of footprints of children or young individuals in such deep spaces in caves with Magdalenian rock art, like La Garma, Tuc d'Audoubert (Pastoors et al. 2021), Montespan (Vallois 1931), Niaux (Pastoors et al. 2015), or Fontanet (Ledoux

2019), or finger flutings, as in Rouffignac (Sharpe and Van Gelder 2006), seems to be relevant evidence in this regard.

Furthermore, the fact that the techniques and degree of finishing of the graphic units (GUs) in the “hidden” clusters are mostly simple, schematic, and/or unfinished is also suggestive, as it might lead to the hypothesis of the presence of artists in the process of initiation and learning (Breuil 1952). However, caution is needed because studies conducted so far in this regard have only detected “inexperienced” individuals associated with portable art (Rivero and Garate 2020). Nevertheless, there is an uneven use of certain types of objects based on experience (Rivero 2016, 2021). In this sense, it should not be ruled out that the “awkwardness” or “simplicity” of these GUs in the cluster of “hidden” figures may have other more practical explanations, such as resource economization. It is logical that in deeper areas, artists would use simple techniques or create unfinished figures to make the

most of limited illumination resources (Medina-Alcaide et al. 2021), whereas in areas closer to entrances, this may not be as necessary. In fact, Cluster 3, composed of figures made in clay (a technique that can yield spectacular results in terms of visibility in a short time), is almost exclusive to very deep and distant areas, while the “visible” clusters (which often include combinations of techniques and more detailed figures, requiring a greater investment of temporal resources) are more typical of areas closer to entrances. Other types of techniques that require longer working times, such as deep engravings made through abrasion or pecking, or sculptures in hard materials, are almost exclusive to sunlit areas like rock shelters and open-air rocks, or parts of caves located in semi-darkness, as in Coímbre (González Pumariega 2020) or Isturitz (Garate et al. 2016b). In fact, this is the reason for not including the latter cave in our study (no figurative rock art examples in dark areas).

To conclude, it is necessary to acknowledge that both the analysis of spatial parameters and statistics have certain limitations that must be taken into account. In the case of GIS, these tools are valuable in archaeology for their ability to interpret the terrain, even in three-dimensionally complex spaces such as caves (Landeschi 2019; Landeschi et al. 2016, 2019; Polig et al. 2020). However, they are not tools designed *ex professo* for this type of environment (Ortega 2014) and have a series of issues that need to be considered for a proper assessment of the results, such as the inability to account for psychological factors (such as vertigo produced by exposure to vertical drops) that may have affected Magdalenian individuals that traversed and decorated these places.

Regarding statistical studies, several issues need attention, such as those related to the selection of study sites. For example, our selection has led to the numerical weight of bison (201 individuals, 40.2% of the total) being considerably higher than that of horses (91 individuals, 18.2% of the total). Although this representativity is statistically expected for the Magdalenian period in the region (Sauvet 2019; García-Bustos and Rivero 2023), the inclusion of sites like Armintxe (González Sainz 2019/20), Oxocelhaya, or Erberua (Larribau 2013), for which we do not have three-dimensional documentation for this purpose, would have balanced the proportions between the two themes. Moreover, the selection of caves with very high values of accessibility difficulty, such as Etxeberri, or highly unequal developments (for example, Atxurra with figures far from the entrance, in contrast to the rest of the sites with decorated sectors in the first 100 m of the cave), has impacted on the definition of some clusters. It would be interesting to conduct future studies in caves with figures located in very distant areas from the entrance, such as Cullalvera, Niaux, or Rouffignac (with graphic units more than 1 km from the entrance), to study their impact. Finally, in this study, we have prioritized the individual study of the graphic units over that of the panels

since, although it seems evident that compositional units or associations between figures existed (e.g., Sauvet and Włodarczyc 1995, 2000/01), it is challenging to demonstrate whether two or more figures are synchronous (created at the same moment), symbolically interconnected, or if there were different associations or functions for the same graphic unit over the time of cave use (Sieveking 1997).

## Conclusions: multifunctional cave art during the Magdalenian?

The interpretation of the FAMD and HCPC analyses obtained in the study of spatial parameters related to Magdalenian rock art around the central Bay of Biscay indicates the existence of at least four groups of figures within the caves, based on their icono-topographic characteristics.

Two of the groups appear to be antagonistic in terms of their function. On one hand, there is a group of figures that exhibit iconographic and spatial characteristics that facilitate their visibility and understanding by other members of society. These are complete, realistic, and detailed representations, primarily located in areas with relatively uncomplicated access and not too far from the cave entrance. On the other hand, there is a group of figures that seem to have been intentionally created with a very different motivation to hide or make their location and visibility difficult. These are often challenging to identify, incomplete, and situated in places far from entrance points. The other two groups correspond to technical features (engravings and modelling on very soft surfaces like clay) and themes (ideomorphs) specific to these spatial environments, the deep caves.

These results demonstrate the existence of multifunctional graphic activity in the Magdalenian communities that inhabited southwestern Europe between 18.5 and 13.5 thousand years ago, at least concerning the cave art decorating the deep sectors of caves. Interpreting the social aspects of this particular symbolic activity is more challenging. Certain more public uses, intended for the social diffusion of a message, could coexist with other more restricted or personal activities, linked to rites of passage or learning. In fact, clusters of “hidden” parietal figures tend to appear predominantly on low surfaces, even in large galleries that do not necessitate that specific placement. Finally, there also seem to be specific technical preferences based on the topographic location of the drawings. More complex techniques that require more time investment are more common in areas near entrances, while quicker techniques, such as simple engraving or working with clay, would be relegated to the more remote areas of the caves.

All these data emphasize the idea that there was prior planning before decorating the caves (Garate et al. 2023), and therefore, cave art was not randomly placed in the



depths of the endokarst. This planning is expressed in various ways, not only through the chosen themes as established by structuralism (Leroi-Gourhan 1965) but is also present in other aspects such as the selection of the space to be decorated, the technical resources used, the degree of completion of the figures, their height above the floor, or their level of accessibility. In essence, graphic production emerges as an extremely complex symbolic activity with a clear multifunctional character based on our results.

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**Data availability** Data sets, as well as Python script and The R codes used to perform all the analyses reported in this manuscript are available on GitHub (<https://github.com/inakiintxaurbe/spatial-organization-patterns-related-to-magdalenian-cave-art>). Due to the impossibility of uploading the files used to analyze the 500 GU because of their weight, the three-dimensional material and the outputs of the spatial study are accessible upon reasonable request. In any case, some partial files can be consulted at the following link: [https://github.com/inakiintxaurbe/GIS\\_Test\\_Santimami-e\\_Old\\_Chamber\\_of\\_Paintings](https://github.com/inakiintxaurbe/GIS_Test_Santimami-e_Old_Chamber_of_Paintings).

## Declarations

**Competing interests** The authors declare no competing interests.

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