



# Application of Line of Sight and Potential Audience Analysis to Unravel the Spatial Organization of Palaeolithic Cave Art

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## Abstract

The endokarst landscape is the result of long erosion and sedimentation processes that have modelled an environment in which capricious forms abound. Despite being a hostile environment for human life, these caves must have attracted the attention of human groups from as early as the Palaeolithic. It is striking that many examples of rock art appear to be closely symbiotic with their natural support; nevertheless, it is difficult to confirm any relationship in the distribution of the decorated spaces, based on their morphology. Moreover, if we start from the hypothesis—widely accepted, but not demonstrated—that Palaeolithic cave art is a system of visual communication, the visibility of the art or the number of people who could be accommodated in the decorated sectors should be determining factors. In order to avoid making subjective appraisals when analysing these factors, we have designed a Python script with a workflow to work directly with 3D models of caverns using GISs, which can be easily replicated and edited by other researchers. Application of this script in the Magdalenian caves of Atxurra, Santimamiñe and Altxerri (Northern Spain) has allowed us to compare them accurately based on their visibility features. This has shown that in some cases, there may have been prior planning to enhance the visibility of some figures. In all cases, the groups of figures are located in deep and hidden parts of the caves, usually in sectors with limited capacity to accommodate people, which would be consistent with a system of restricted communication.

**Keywords** Cave geomorphology · Inner archaeological context · Magdalenian · Visibility · Capacity · GIS

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## Introduction: the Role of the Cave in the Spatial Organization of Palaeolithic Rock Art

Despite the difficulties in ascertaining the cultural and/or religious motivations behind Palaeolithic rock art (Bahn, 2011; Conkey, 1996; Sauvet *et al.*, 2009), there are numerous examples that enable us to determine the place of graphic production in the socio-economic behaviour of these populations (Fritz, 1999; Rivero, 2010; 2017; Fritz *et al.*, 2016a). We can assert that a form of organization existed in relation to artistic production, in relation to learning and transmission inside and between social groups (*e.g.* Rivero, 2016; Rivero & Garate, 2020). The homogenous motifs, techniques and stylistic features of Upper Palaeolithic art offer enormous potential information on networks of exchange of cultural knowledge (Sauvet, 1990, 2019; Jaubert & Barbaza, 2005; Bicho *et al.*, 2007; González-Sainz, 2007a; Utrilla & Martínez-Bea, 2008; Sauvet *et al.*, 2008a, 2008b, 2018; Rivero & Sauvet, 2014; Rivero *et al.*, 2014; Villaverde, 2015; Sauvet & Rivero, 2016; Petrognani & Robert, 2019; Domingo & Roman, 2020) that did not necessarily operate at the same time as the networks of technological exchange. If one accepts the social function of rock art as a visual communication system (Dobrez, 2016; Domingo *et al.*, 2016; Porr, 2010), it could have functioned either as an open (public, accessible) or closed (private, restricted) system. Thus, these social groups could use the natural resources (*i.e.* the morphology of the caves) either to increase the prominence of the figures or, by contrast, to conceal them. A formal analysis of these possible spatial patterns in rock art would enable a more profound understanding of the degree of complexity derived from symbolic actions in past societies (*e.g.* Baptista *et al.*, 2008; Domingo *et al.*, 2008; Baptista & Santos, 2010), in addition to other factors (economic, technological or cognitive, *etc.*) (*e.g.* Fiore, 2020).

Caves attracted human populations from at least the Middle Palaeolithic (Jaubert *et al.*, 2016), and particularly during the phases of the Upper Palaeolithic, when the archaeological record increases considerably. They often show a contextual relationship with rock art (Clottes, 1993; Medina-Alcaide *et al.*, 2018). These peculiar sites are usually found in karstifiable chemical sedimentary rocks and are often the result of long and varied processes of erosion and sedimentation that can form different features throughout the cave (Ford & Williams, 2007). Additionally, the rock in which the cave is located can have specific characteristics (*e.g.* nodules, stratification, fractures) that tend to favour the presence of particular forms and shapes (prominent areas, flat surfaces, *etc.*) (Palmer, 2007). Since the mid-twentieth century, some authors (*e.g.* Laming-Empeaire, 1962) have insisted on the role of the cave in the structure and composition of Palaeolithic art, especially A. Leroi-Gourhan (1965) who coined the term *la caverne participante* to describe this phenomenon. Other authors disagree somewhat in their interpretation, arguing that the cave had a greater role as an *organisatrice* than a *participante* entity (Lorblanchet, 1994; Pigeaud, 2013). Nonetheless, there is general consensus that the distribution of cave art is usually strongly influenced and conditioned by the prevailing topography and morphology of the cave (*e.g.*

Lejeune, 1985; Sanchidrián, 1990; Lorblanchet, 1995, 2010; Sieveking, 1997; Sauvet & Tosello, 1998; González-García, 2001; Bahn, 2003; Vialou, 2004; Villeneuve & Hayden, 2007, Garate, 2010; Ruiz-Redondo, 2014; González-Sainz, 2007a, 2007b; Robert, 2007, 2009, 2011, 2017; Sauvet & González-Pumariega, 2017; Ochoa & García-Diez, 2018; Jouteau *et al.*, 2019a; Sakamoto *et al.*, 2020).

This does not mean that all cave decorations of the Upper Palaeolithic follow a single universal pattern, as proposed by A. Leroi-Gourhan (1965). However, one must assume that a single cultural group might leave a non-random artistic organization in different caves, which might perhaps be determined from the archaeological and artistic record (Laming-Emperaire, 1962; Leroi-Gourhan, 1965; Vialou, 1986; Sanchidrián, 1992; 1994; Sauvet & Włodarczyk, 1995; 2000–2001) and/or from the placement patterns of the decoration. There are also alternative theories, according to which rather than a graphic tradition there was a “bricoleur”, and similarities (or stable iconography) are explained more by contiguous than continuous practices (Conkey & Fisher, 2020). We must wonder whether such theories would suggest an infinite number of possibilities for the topographic decoration of caves or whether, on the contrary, there might have been certain specific patterns for this purpose (perhaps taken from contiguous practices).

At the same time, caves are natural environments, and therefore, unlike other archaeological elements—such as spear throwers or bone disks—there is a randomness in the arrangement of the “decorative” spaces they contain. That is to say, no two caves are identical, because each has had its own erosive and sedimentation processes, and characteristics of the bedrock are mostly different. Furthermore, the same sedimentary and erosive processes can completely alter the topography of a cave over a short (Van Gundy & White, 2009) or long period (Laureano *et al.*, 2016). To these issues, one might add the taphonomic problems of biological (Audra *et al.*, 2019; Bruxelles *et al.*, 2016) and human origin, including prehistoric morphological changes (*e.g.* Geneste, 2001; Balbín-Behrmann *et al.*, 2003; Arias *et al.*, 2004). This makes it necessary to perform different types of geoarchaeological study as a means of supporting archaeological interpretations (*e.g.* Canti & Huisman, 2015; Delannoy *et al.*, 2020).

Formerly, one of the main problems involved in this type of research was the subjectivity resulting from the necessary use of qualitative terms, which could make the opinions generated by each author very different. In recent years, these problems have been solved with the emerging use of digital methods that have made spatial analyses more accurate (*e.g.* Jouteau *et al.*, 2020; Intxaurbe *et al.*, 2021). Geographic Information Systems (GISs) have been widely used in “sensorial” archaeology and interactive documentation, due to their precision and ability to interpret the terrain (Wheatley & Gillings, 2000; 2002; Wheatley, 2004; Llobera, 2007; Gillings, 2015; Díaz-Andreu *et al.*, 2017; Wernke *et al.*, 2017; Wienhold & Robinson, 2017; Lesvignes *et al.*, 2019), with all their strengths and limitations, as previously identified (Boche *et al.*, 2012, 2014; Frieman & Gillings, 2007; Gillings, 2017; Llobera, 2012; Ogburn, 2006; Van Leusen, 1999). These techniques are usually employed in open-air studies, but there are some specific precedents in closed and three-dimensionally complex sites (Landeschi, 2019; Polig *et al.*, 2020), including caves (Ortega, 2012, 2014) and rock shelters (Bourdier *et al.*, 2017a). An analysis of the study using GISs

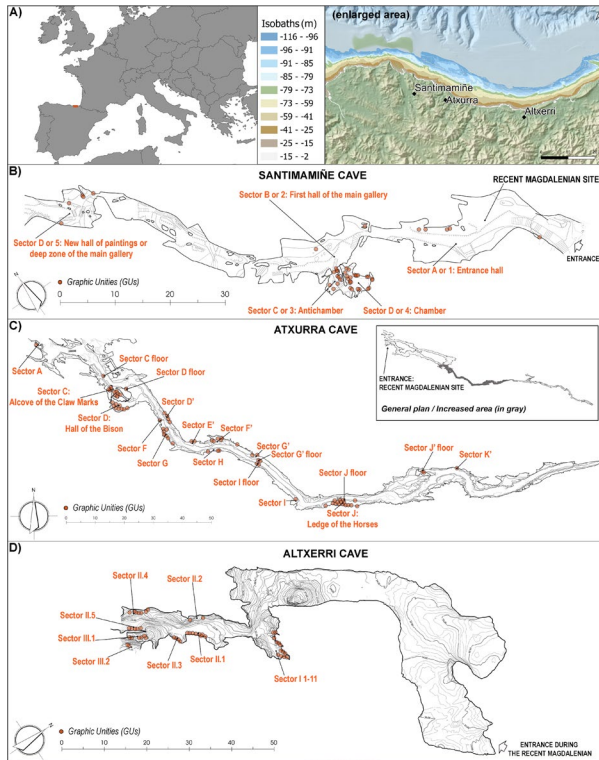
of the viewshed of each graphic unit (GU) in Atxurra cave has previously been presented (Intxaurbe *et al.*, 2020), confirming a strong correlation between the location of certain GUs inside the cavern and their visibility. One of the most successful analytical platforms directly uses the 3D mesh for Line of Sight (LOS) analyses in these types of enclosed environments (Dell'Unto *et al.*, 2016; Landeschi *et al.*, 2016, 2019; Landeschi, 2019).

### **Materials: Middle/Upper Magdalenian Cave Art on the Eastern Cantabrian Seaboard**

Given the large number of decorated Palaeolithic caves in SW Europe (at least 450 caves or rock shelters, not counting open-air sites), with a wide variety of chronologies, technical and thematic resources and topographic layout, we have decided to limit our research geographically and chrono-culturally. For this reason, we have searched for synchronic decorated caves on the Eastern Cantabrian seaboard (Northern Spain), in an area with an abundance of archaeological sites of Middle/Upper Magdalenian chronology (Arribas, 2005; González-Sainz, 1989). The fact that they belong to the same geographical context also means that they may have been influenced by the same environmental changes; while this does not necessarily imply that the geological evolution of the caves was the same, it does serve to reduce their casuistry.

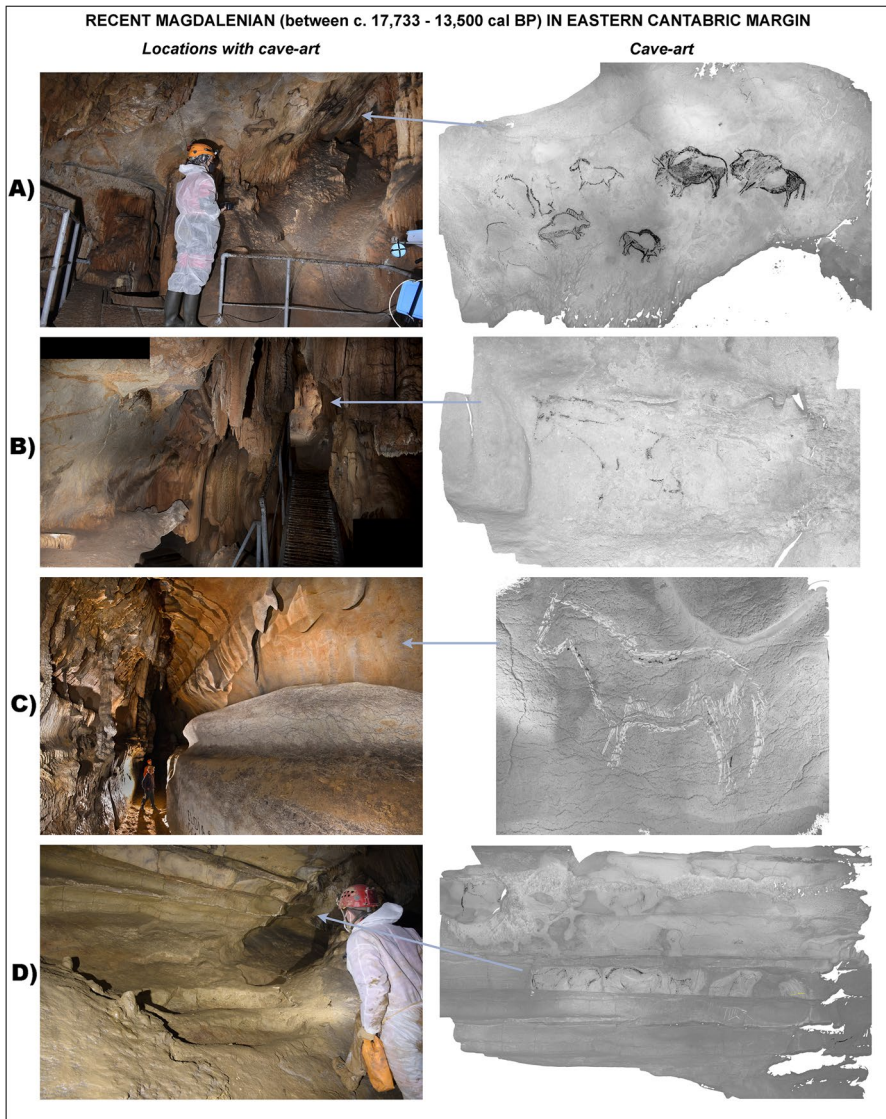
Magdalenian culture developed widely across SW Europe (*e.g.* Breuil, 1912; Utrilla, 1981; González-Sainz, 1989; Angevin, 2012; Bicho & Haws, 2012; Román & Villaverde, 2012; Pétilion, 2013; Bourdier *et al.*, 2017b; Ivanovaité *et al.*, 2020; Maier *et al.*, 2020), with inter-regionally shared traditions (including possible similar behaviours regarding subterranean appropriation). However, differences—both thematic (*e.g.* M. García-Bustos, 2019a), stylistic and technological—can be seen between regions, owing to the fact that there would have been three tiers of exchange network (Fitzhugh *et al.*, 2011; Fuentes *et al.*, 2019a; Sauvet, 2019): “local networks” comprising a few members of a community; “regional networks” made up of several local networks; and finally “supra-regional networks”, allowing communication between distant groups. As a result, for example, on the Cantabrian seaboard, Magdalenian artists tended not to overlap figures on the same walls, while in other European areas (*e.g.* the Pyrenees, Aquitaine), this arrangement is more common (González-Sainz & Ruiz-Redondo, 2010).

In chronological terms, it is accepted that the more recent (Middle and Upper) phases of Magdalenian culture in the region developed between c. 17,733 and 13,500 cal yr BP (Arribas, 2005; González-Sainz & Utrilla, 2005). There are several examples of portable art in this region (Garate *et al.*, 2015; Rivero, 2010), including at least ten caves with rock art (Garate, 2017; 2018). In addition, the sea level was 60–70 m lower than at present, and the coastline would have been 2.5–4.7 km further out (Lambeck *et al.*, 2014) (Fig. 1), and there is evidence of some carbonated lithologies in this submerged area of the coastline on the Eastern Cantabrian seaboard (Vanara *et al.*, 2007). Therefore, there might also be submerged sites that may have contained archaeological deposits or rock art. In general terms, the stratigraphical



**Fig. 1** Studied cave sites. **A** Their location in SW Europe (left) and in Eastern Cantabrian seaboard. The coastline has been moved to its position during the Upper Magdalenian (60–70 m below the current one), showed by the cream/green colour in bathymetries (sources: <https://ec.europa.eu/eurostat/>, <https://www.gmrt.org/GMRTMapTool/>, <https://www.geo.euskadi.eus/>). This position could vary slightly due to sedimentary bodies near each river mouths (Jouanneau *et al.*, 2008; Galparsoro *et al.*, 2010). Plans of studied caves, showing their supposed entrances during the recent Magdalenian, and the location of the known rock art. **B** Santimamiñe cave (I. Latasa, K. Zuloaga and A.D.E.S.). **C** Atxurra cave (Gim-Geomatics and A.D.E.S.). **D** Altxerri cave (L.C. Teyra over CRN surveying data)

data makes it possible to assign certain stylistic conventions of some figurative representations to a specific phase. For example, the convention of the frontal view in the ibex is typical of Upper Magdalenian phases (Rivero *et al.*, 2014). In other conventions, however, it is more difficult to distinguish between the middle and upper phases (González-Sainz, 2007b; Sauvet & Rivero, 2016). Briefly, it may be noted that during the recent Magdalenian, there is a tendency in this region to seek realism and to increase the level of detail in the figures (Ruiz-Redondo, 2016). Examples of this include the perspective in different planes (especially in extremities and horn-like appendages) and the marking of different volumes of pelage (Fig. 2). However, there are great differences (primarily in the themes) between the graphic elements on portable and parietal supports. For example, during the recent Magdalenian, there is a near absence of bison figures in portable art in the region—they are found practically only on the portable supports from the Middle Magdalenian phases in



**Fig. 2** Tracings of analysed cave art (right), showing its locations inside the caverns (left). **A** Santimamiñe cave. “Chamber” of paintings and the main panel. **B** Santimamiñe cave. “New hall” of paintings and horse San.5.2.1. **C** Atxurra cave. “Ledge of the horses” (author: X. Gezuraga) and horse Atr.J.II.65 (O. Rivero, J.F. Ruiz-López and D. Garate). **D** Altxerri cave. “Frieze” of sector II.4 and panel Alt.A.II.4

Las Caldas (West Cantabrian) and Isturitz (on the western border of the Pyrenees)—whereas they are among the most numerous themes on parietal supports (including those studied in this work) (Sauvet & Rivero, 2016) and are found both in the middle (*e.g.* La Garma, Alkerdi, Aitzbitarte V) and upper phases, with an example directly dated in Urdiales cave at  $12,750 \pm 110$  uncal yr BP (15,901–14,545 cal yr

BP) (Valladas *et al.*, 2013). As for the locations of the rock art inside the caverns, the Eastern Cantabrian coast (in addition to the Western Pyrenees) contains several sites with recent Magdalenian art in locations that are paradigmatic in terms of their difficulty of access, such as Aitzbitarte IV (Garate *et al.*, 2020b) or Etxeberriko Karbia (Garate & Bourrillon, 2019).

In addition, we have also selected caves that were three-dimensionally scanned (indispensable for the purpose), numerically representative (containing more than 50 figurative GUs, including animals and complex signs) and for which documentation has recently been published (presumably containing the most updated catalogue of rock art).

Using these criteria, we selected three caves (Fig. 1): Santimamiñe (Aranzadi *et al.*, 1925, 1935; Barandiarán, 1976; González-Sainz, 2009; González-Sainz & Ruiz-Idarraga, 2010; A.D.E.S., 2010; López-Quintana, 2011), Atxurra (Barandiarán, 1961; Fernández-Eraso, 1985; Garate *et al.*, 2016, 2020a; Rios-Garaizar *et al.*, 2019; 2020) and Altxerri (Barandiarán, 1964; González-Sainz *et al.*, 2013; Ruiz-Redondo, 2014; Ruiz-Redondo *et al.*, 2017), all of which were decorated during the recent period of the Magdalenian chrono-culture (a more detailed explanation of the caves can be found in [Supplementary Materials](#)).

These caves contain technically and stylistically synchronous sets, but it is more difficult to ascertain whether they were executed in a single event, or over a longer period (*e.g.* a decoration created over a number of generations versus an activity performed in a few hours or days). This could be solved with a traceological study of the figures (Semenov, 1964; D'Errico, 1994; Fritz, 1999; Rivero, 2007; P. García-Bustos, 2019b), which could show the use of certain tools to execute the GUs, or help determine the presence of specific artists, despite the difficulty such an approach entails (Apellániz, 1987; Groenen & Martens, 2004). This would be important, given that even if we could confirm whether or not there was prior planning (Gittins & Pettitt, 2017), we do not know whether there was a single previous exploration of the natural cave (Rouzaud, 1990), with all the complexity that would have involved in terms of memorizing the topographic and morphological structure of the cave, or whether the current decoration was the result of small, successive additions over time.

## Methodology: Use of GIS for Visibility and Potential Audience Analyses

We have adapted the visibility analysis proposed by Landeschi *et al.* (2016), adding several points for use in endokarst environments based on the data obtained from experimentation with Palaeolithic lighting systems (Medina-Alcaide, 2020; Medina-Alcaide *et al.*, 2021), and updating it with an estimation of the human capacity (number of persons who could be accommodated) based on the measures proposed by Pastoors and Weniger (2011). Our ultimate purpose is to define a method that allows researchers to analyse certain features of the spatial distribution of cave art, in order to confirm whether there was really a predisposition to organize certain panels (or groups of panels) with Palaeolithic rock art based on the visual prominence

of the natural supports or the capacity of the decorated areas. Our method consists of using three-dimensional models of the caves (previously modified to reflect their condition when they were decorated), and entering them in ArcMap™ by ArcGIS® as a *wrl* file, to create different raster files (Scott & Janikas, 2010), following a defined procedure (Opitz & Nowlin, 2012). These are analysed using the Lines of Sight technique, obtaining frequency maps for potential observers, and target points (parts of the surface that contain rock art, or the GUs themselves). In addition, we will determine the maximum capacity for each space from which the different figures are visible, based on different levels of visibility. We have summarized this workflow in a Python script for ArcGIS® (see <https://github.com/inakiintxaurbe/lineof-sight-and-potential-audience-analysis-to-cave-art>), including the parameters we used in our analysis. In any case, this script is easily editable and can therefore be adapted for other different cases, including new variables and parameters that could have an effect on the visual perception itself, such as reflectance (de Beaune, 1987; Delluc & Delluc, 1979a; Jouteau *et al.*, 2019b, 2020) and psychological perception (Opitz, 2017).

### Recreating the Geomorphology of the Caves

The caves were first scanned using a terrestrial laser scanner, from CRN, Virtualware and Gim-Geomatics. The use of 3D technology is now relatively common in underground Palaeolithic art research (*e.g.* Fritz & Tosello, 2007; Lerma *et al.*, 2010; Domingo *et al.*, 2013; Hoblea *et al.*, 2014; Bourdier *et al.*, 2015; Fritz *et al.*, 2016b; Jaillet *et al.*, 2018; Ruiz-López *et al.*, 2018; Fuentes *et al.*, 2019b; Rivero *et al.*, 2019). However, it is very important to remember that karsts systems have also been undergoing continuous changes since their prehistoric occupation. Bearing this in mind, and taking advantage of the possibilities of this technology, we can perform different studies (accessibility, capacity, visibility, *etc.*) with a model as close as possible to the site that the prehistoric societies would have found at that time (Arriolabengoa *et al.*, 2020; Delannoy *et al.*, 2010, 2020; Genuite *et al.*, 2021; Sadier, 2013).

In short, the artwork in the sanctuaries of these three caves can be assigned—by stylistic comparisons and/or contextual dating—to the final of MIS 2 (c. 17,700–13,500 cal yr BP). Since these caves were decorated, there have been erosive events—usual in the area in interglacial-glacial transitions (Aranburu *et al.*, 2015; Arriolabengoa *et al.*, 2018, 2020; Stoll *et al.*, 2013)—such as those observed in the vestibule of Santimamiñe, where the episode of Almp's stratigraphic alteration might have occurred within the Alleröd oscillation (c. 14,000–13,500 cal yr BP) and/or Preboreal (c. 11,270–11,210 cal yr BP) (López-Quintana, 2011). In any case, further regional paleo-climatic studies are required to confirm these propositions (*e.g.* Bernal-Wormull *et al.*, 2021). Lithochemical sedimentation events also occurred during the Holocene, obstructing formerly wider passages, such as those observed in Atxurra (Arriolabengoa *et al.*, 2020). In Altxerri, one should mention certain specific collapses that occurred in the cave due to the particular lithology of the karst, such as those that sealed the entrances, caused the enlargement of the first hall or detached the piece of wall/roof that contained the group of figures Alt.A.1.11



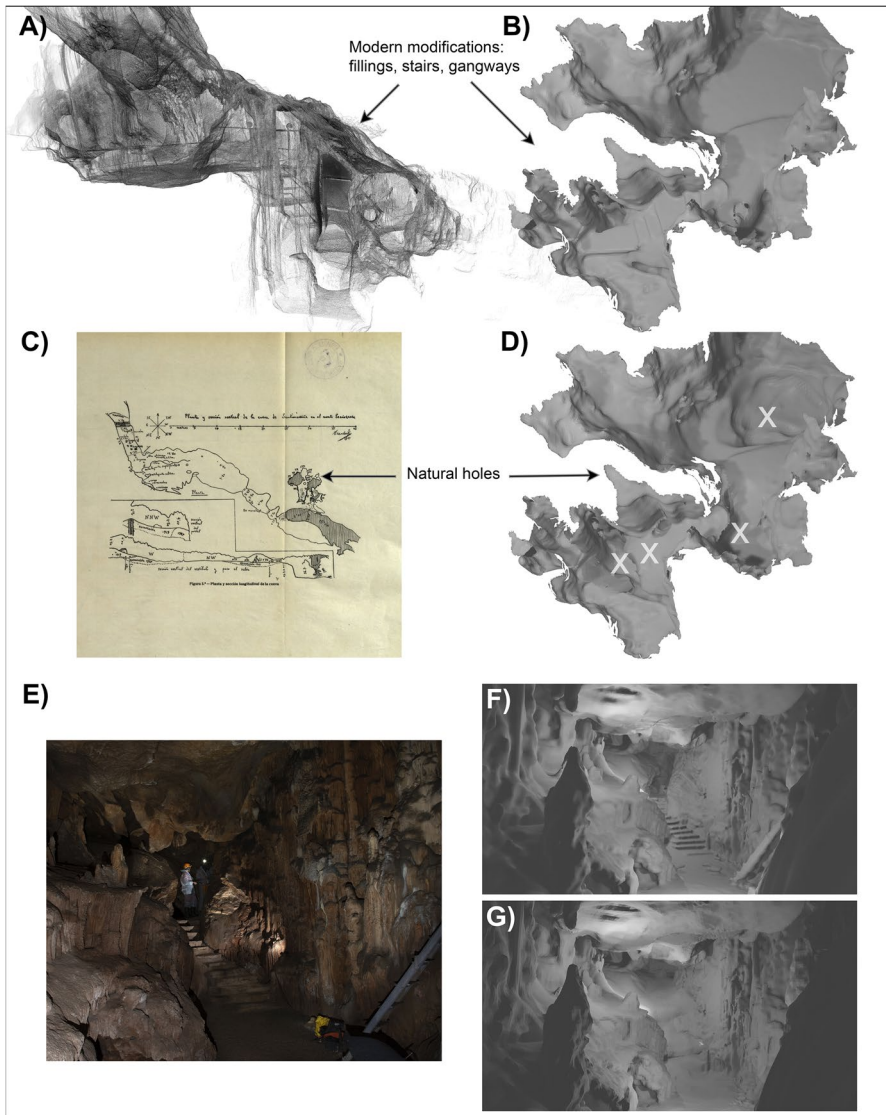
(Barandiarán, 1964; Ruiz-Redondo, 2014). On the other hand, all three caves have suffered anthropic alterations in recent times, sometimes related to their adaptation for tourist use, widening passages and building walkways and ladders (Santimamiñe); facilitating access for researchers, carving footholds (Altxerri); or vandalism and uncontrolled visits (visible in all three caves, but especially dramatic in Atxurra). In any case, we should note that in this approach, we have taken into account alterations at a macro-taphonomic level. We are currently carrying out micro-morphological studies in the caves that will enable us to determine any alterations in each decorated surface (*e.g.* Le Fillâtre *et al.*, 2021). The results of these studies will make it possible to establish whether the current graphic ensemble differs from any that may have existed before.

Our 3D models have subsequently been modified, on the basis of morphological data obtained from geological studies (*e.g.* Arriolabengoa *et al.*, 2020) and comparing older and more recent graphic documents, taken from the data of early explorers (*e.g.* Aranzadi *et al.*, 1925; Barandiarán, 1964), using Meshlab® (to cut and work independently in areas of interest) and Blender®. We used the “Sculpting mode” to reduce and cut out Holocene formations or recent anthropic modifications; relocated the fallen rock containing the Alt.A.I.11 group in Altxerri, separating it from the 3D model and then merging it in its original location; and added currently missing surfaces (*e.g.* to reconstruct the original sedimentary and lithochemical fillings in Santimamiñe), thus creating new plans and then sculpting them (Fig. 3).

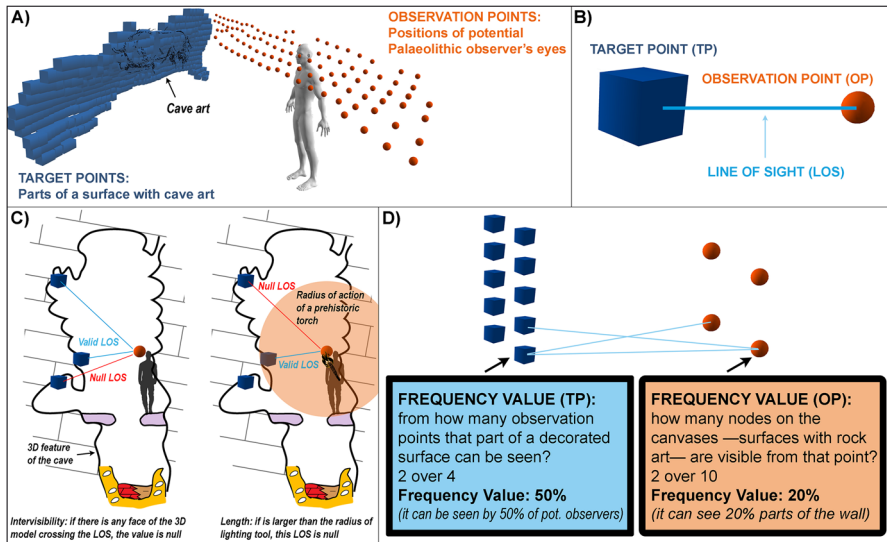
## Line of Sight Analysis

Line of Sight (LOS) analysis is based on the construction of segments starting from an observation point (OP) (*e.g.* a potential Palaeolithic visitor) and ending in the observed target point (TP) (*i.e.* a GU). If any object (*i.e.* the modified 3D model of the cave) intersects the line, it is considered an obstacle, and the line of sight is null (Fig. 4). In establishing possible observation points of the panels, we discarded sites with steep topography. By experimenting with cavers and other people accustomed to working in caves (biologists, archaeologists and geologists) to assess the difficulty of prehistoric cave transit, we estimate that a person can transit upright or in a crouched position on surfaces with angles of up to 45° (Intxaurbe *et al.*, 2021). However, we reduced this maximum inclination of 30° using the “set null” tool, in order to exclude extremely uncomfortable cases. Exceptionally, these flat surfaces might be extended with the use of scaffolding (*e.g.* Delluc & Delluc, 1979b); however, we have not located any remains attributable to such elements in the caves studied.

The script subsequently uses the average human stature during the European Late Upper Palaeolithic (c. 1.66 m) (Holt, 2003) to establish a fixed position for each observation point. Although such inferences should be treated with caution, given the absence and low representativeness of anthropological remains from these chronologies (LUP), we believe that they serve to establish valid criteria, as shown by recent comparisons with ancient DNA (Cox *et al.*, 2019). We then established two possibilities, depending on the height of the passages, one when the passages are greater than 1.66 m in height (upright position), and another



**Fig. 3** Modification of the 3D model of Santimamiñe cave, to restore its original state. **A** Point cloud of the “Chamber” and “Antechamber”, with the presence of anthropic alterations (doors, artificial floors, handrails, fillings, *etc.*). **B** Upper view of the 3D model showing the current state of the “Chamber” and “Antechamber”. **C** Topography of 1925, showing the state of the cave in that year, prior to the works for the tourist visits. **D** 3D reconstruction of the “Chamber” and the “Antechamber”, to show the original state of it (main changes have been enhanced with an X). **E** Entrance to the first “Hall” of the main gallery, where recent modifications can be seen to facilitate tourist visits: A big flowstone (prior to Magdalenian) was sculpted to made stairs, and the floor was flattened with gravel. **F** 3D model of the current state of the cave. **G** 3D model modified to show its original state during the Magdalenian



**Fig. 4** Brief summary showing the steps of LOS analysis (see [Supplementary Materials](#)). **A** LOS analyses are based on establishing target points (TP), which can be the decorated surfaces, or the GUs itself, and observation points (OPs), which would be the position of potential Palaeolithic audience. **B** A Line of Sight (LOS) is traced between each TP and OP. **C** Some corrections are made, to ensure that the valid LOS are only going to be those which are not intersected by a shape of the cave, and are covered by the radius of action of selected Palaeolithic lighting tools. **D** Frequency values are established, counting how many OPs can see a TP (frequency value TP), or how many TPs can be seen from an OP (frequency value OP)

when the passage height is between 0.71 and 1.66 m (corresponding to a squatting position). The script can be modified to add a third measure (*e.g.* reclining positions), given that other caves with Magdalenian art, such as Alkerdi 1 (Garate & Rivero, 2015), are known to contain very narrow areas with high concentrations of figurative GUs. Once the positions of the potential observers have been obtained, a mesh is created with cells of  $0.25 \times 0.25$  m, from which the OPs are extracted automatically (in the estimated position of the potential Palaeolithic observers' eyes) (Fig. 4).

Once the OPs have been obtained, the script delimits the area of analysis creating a buffer (using the “Buffer” tool) from the GUs based on the radius of action of a selected lighting tool (see [Supplementary Materials](#)). This is used to determine from what distance the walls on which the GUs are executed would begin to be visible. The lighting systems taken into account are torches, tallow lamps and hearths at the foot of the panels (de Beaune, 1987, 2000; Galant *et al.*, 2007; Medina-Alcaide, 2020; Medina-Alcaide *et al.*, 2015, 2021; Pastoors & Weniger, 2011). If the last option we employed (fixed fires), their position needs to be added, based on archaeological data.

TPs then need to be established to perform the LOS analysis (Fig. 4). To analyse the entire surface containing rock art (regardless of whether a GU has been located), we recommend adding points manually. This can be done in ArcScene™,

by creating a new shapefile and adding points to the 3D feature every 25 cm<sup>2</sup> (see [Supplementary Materials](#)). If we want to analyse the visibility of the GUs directly, we can rename a shapefile with the position of each GU as “TP.shp”.

## Frequency Values

The script uses the “Construct Sight Lines” and “Intervisibility” tools to perform the LOS analyses. The first of these establishes all possible sight lines from the observers (OPs) to the targets (TPs). The second directly uses the 3D model of the cave, to determine which LOSs are obstructed by any feature in the cave (stalagmite, cave-wall, column, *etc.*). If there is direct contact between two points, a value of 1 will be assigned to that LOS. By contrast, if there is an obstacle between the two that prevents direct vision, it will be assigned a value of 0 (Fig. 4). The script will also discard any lines that exceed the maximum radius of action of the mobile lighting tools (Fig. 4). Using the “Select”, “Summary Statistics” and “Count” tools, the script counts all possible interactions between OPs and TPs, thus determining the frequencies of each OP (how many nodes on the canvases—surfaces with rock art—are visible from that point) and each TP (from how many observation points that part of a decorated surface can be seen) (Fig. 4).

The frequencies are used to elaborate a frequency map (using the “From points to raster” tool), with a grid of 0.25×0.25 m cells. Prior to this, the values are normalized to obtain the percentages. Thus, a value of 100% corresponds to observation points from which there is total visibility of the target points (and vice versa). At these points, there is no visual obstacle preventing sightlines to the analysed canvases (Fig. 4). The script also elaborates Kernel Density maps, to observe where the concentrations of highest values are located (*i.e.* the zones with greatest visibility range).

In our case, we previously geolocated the GUs directly on the geo-referenced point cloud (using the free visor of the laser scanner) or in situ (in the cave) using a DistoX2 device (Intxaurbe *et al.*, 2020; Trimmis, 2018). To obtain frequencies maps of the GUs, we took into account the entire graphic ensemble as a reference for calculating percentages (to determine the most visible GU in the cave), but also the composite units (or grouping of figures). In order to use the same criteria (thus avoiding any subjective approaches), we defined groups as those sets that contain figures interspersed at a maximum distance of 2.99 m from one another. This roughly coincides with the radius of action of a prehistoric torch (Medina-Alcaide *et al.*, 2021). Usually, the panels or compositional units are defined by previously morphologically delimited supports. However, we have tried to extend the analysis to larger sets, since we hypothesise that two independent groupings might belong to the same “narration”, if they could be seen at the same time from the same point.

## Capacity Analysis

According to Pastors and Weniger (2011), architect Neufert (1951) estimated that a person occupies an area of 0.77 m<sup>2</sup> when standing and 1.75 m<sup>2</sup> when lying down.

Ruiz-Redondo (2014) proposed an additional measurement of 0.90 m<sup>2</sup> square meters for people sitting or squatting. The script takes the first and the last measurements as a reference (the second measurement can be also added in the script). Having done this, it readjusts the frequency maps, based on their area and the aforementioned measurements, to obtain the capacities (number of people accommodated). These capacities have been classified according to the level of visibility of the potential observers (OPs): low, for a visibility of between 0.01 and 33.33 percent of the GUs; medium, for values of between 33.33 and 66.66 percent; and high, for values of between 66.66 and 100 percent of the decorated surfaces in a sector.

The script will estimate the capacity of the areas from which the GUs selected for the analysis would be visible. At this point, we recommend following the same criteria as in the previous step. Instead of establishing the sector based on subjective appraisals (*e.g.* topographical features), we have defined groups as sets that contain figures interspersed at a maximum distance of 2.99 m from one another, coinciding with the estimated radius of illumination of a prehistoric torch (Medina-Alcaide *et al.*, 2021). In any case, we can perform different measurements and subsequently compare the results.

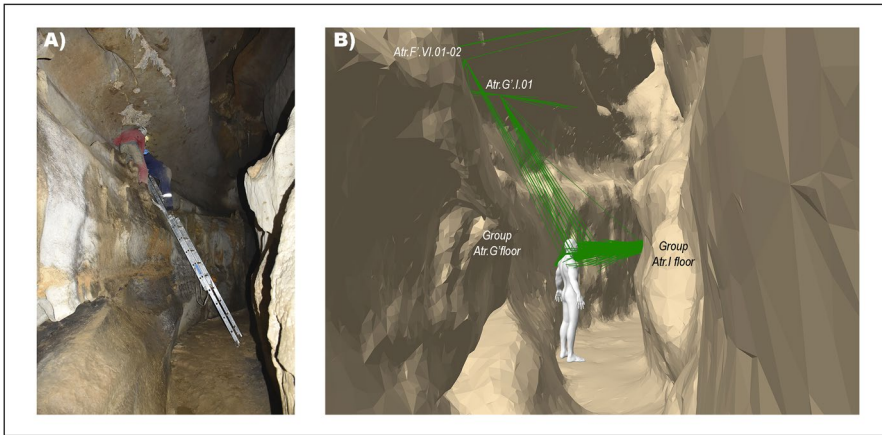
## Results

As previously indicated, the results of this work are conditioned by our specific selection of cases—caves decorated during a specific chronological period (recent Magdalenian) in a specific geographic region (Eastern Cantabrian seaboard). These analyses should therefore be interpreted as minimal descriptive results, used to validate a quantitative methodology for a general understanding of these rock art sets.

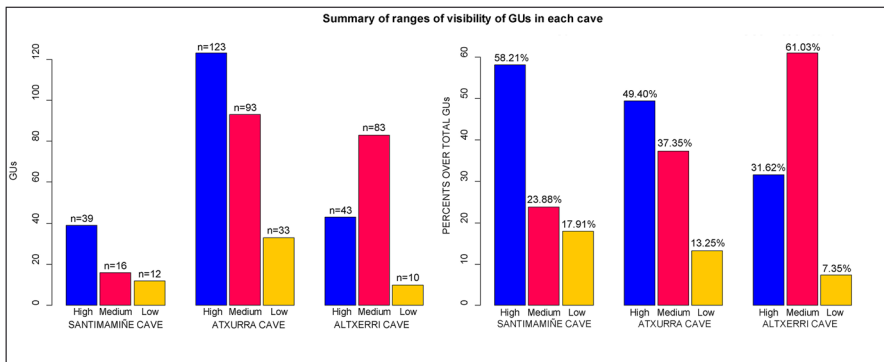
## Visibility

After analysing all the GUs in the caves (with some exceptions which proved impossible to locate due to their state of conservation, or because the 3D models did not cover those sectors), we can state that the LOS analyses appear to support the hypothesis that the morphology of the cave was used by members of a Palaeolithic culture (in this case from the recent Magdalenian in the Eastern Cantabrian region) to enhance some of their artworks (see [Supplementary Materials](#)) (Fig. 5). This behaviour has already been noted by other authors (*e.g.* Lorblanchet, 1993; Ferrier *et al.*, 2017).

All three caves score a majority of medium–high visibility values for the emplacement of their GUs (Figs. 6 and 7). In Santimamiñe, 58% registers high visibility (can be seen by more than 66.66% of potential visitors of a sector), since the main group of figures in the cave (the so-called Chamber of Paintings) are visible from all points in this chamber. The arrangement in Atxurra is similar, but with a higher number of medium (33.33–66.66%) values, because almost all sectors contain narrow sites into which only small groups could enter. In Altxerri, the values are also high, but there is a majority of medium values, because in the main ensemble of figures in the cave



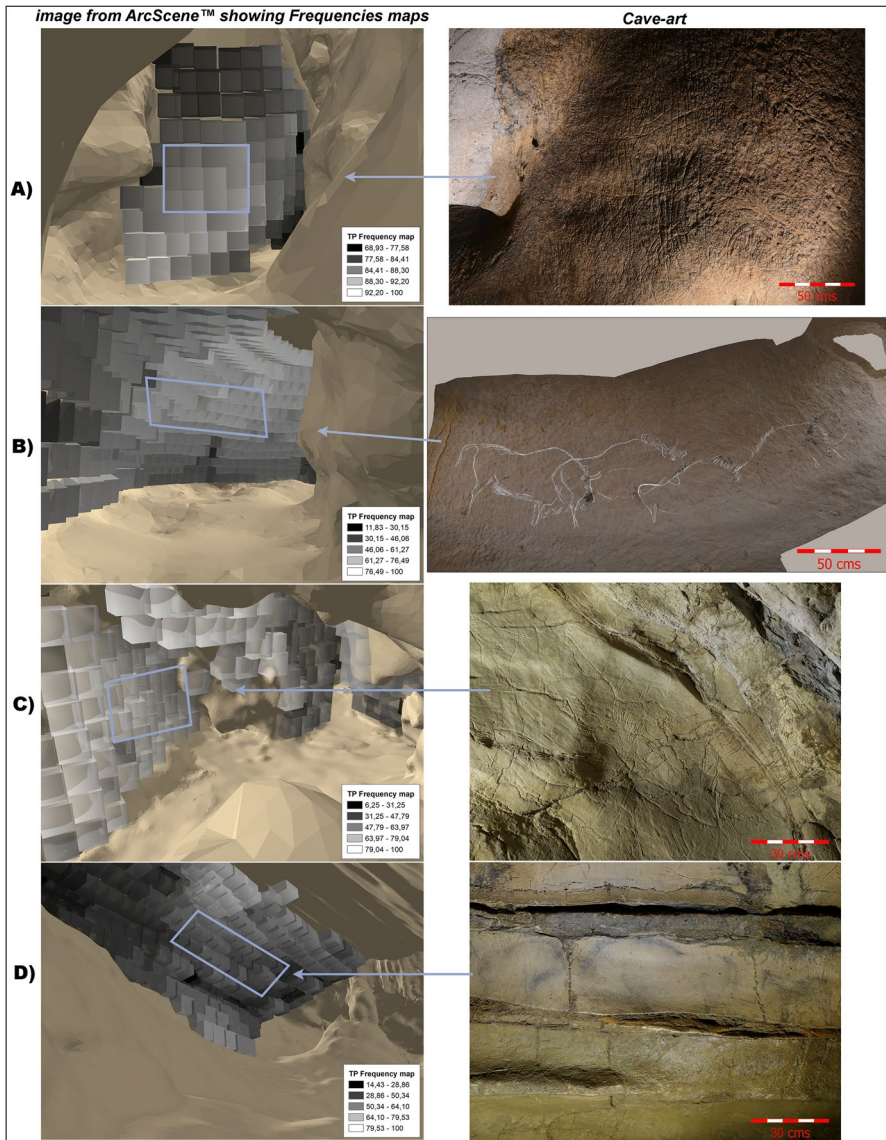
**Fig. 5** An example of some selected LOS in Atxurra cave. **A** Photography of sectors F'-VI, G', G' floor and I floor. The first two are placed in the high parts of the walls, being necessary a ladder to reach them. The last two are placed on the both walls of the lower part of the passage, where the natural thoroughfare towards the back of the gallery goes. **B** Image extracted from ArcScene™, showing the selected LOSs. A potential Palaeolithic visitor has been put in the image to show the potential location of their eyes. With the light of a torch, he might see all decorated surfaces from the lower part of the passage



**Fig. 6** Comparison of the GUs analysed in Atxurra, Santimamiñe and Altxerri, according to their visibility values (bar graphic made with R, see [Supplementary Materials](#))

(known as “I”), most GUs are located in a side passage and are only visible to small groups entering there. In any case, it is important to bear in mind that we are only analysing the visual prominence of the artistic supports. Other factors would also have influenced visibility, such as the size of the figures, the technique (or combinations used) (Fig. 7), *etc.* 8.

Previous works have suggested that “hidden” figures tended to be smaller in size, or more “simplistic” (unfinished, monotechnic, schematic, *etc.*) (Villeneuve & Hayden, 2007; Ruiz-Redondo, 2014; González-Sainz, 2017; Intxaurbe *et al.*, 2020). However, we have detected some striking cases of complex figures (in terms of



**Fig. 7** Several examples of frequency maps for the decorated canvases. Atxurra cave: **A** GUs Atr.C.I.1–5 were emplaced in sites with very high visibility (O. Rivero and S. Salazar). **B** GUs Atr.D.V.I-6 are emplaced in a prominent site of the wall, in the corner produced between the wall and ceiling (O. Rivero and M. Cobo). Altxerri cave: **C** GUs Alt.A.I.3.15–16 were engraved in a site with high rates, with two planes, and where the support evokes the shape of a reindeer (GFA—J. Latova). **D** GUs Alt.A.II.4.8–10 are placed in a site with medium values of visibility, but conditioned by the morphology of the canvas (GFA—J. Latova)

**Fig. 8** Comparison of the analysed sectors, according to the level of visibility of the potential observers (OPs): low, for a visibility of between 0.01 and 33.33% of GUs (in yellow); medium, for values of between 33.33 and 66.66% (in magenta); and high, for values of between 66.66 and 100% (in blue). **A** Santimamiñe cave (with a detail of the “Chamber of Paintings”). **B** Atxurra cave (with a detail of Sectors C and D or “Alcove of Claw Marks and “Hall of the Bison” and J or the “Ledge of the Horses”). **C** Altixerri cave. The maps have been made in ArcMap™

combination of techniques or degree of finish) in sites with low/medium visibility values (less than 66.66%, and even some below 33.33%) (Fig. 7), for example, in some GUs at Altixerri, where despite not being the parts of the supports with the highest rates of visibility, the special nature of the lithology (stratified bedrock) conditions the space available for engraving and painting (Aranburu *et al.*, 2017).

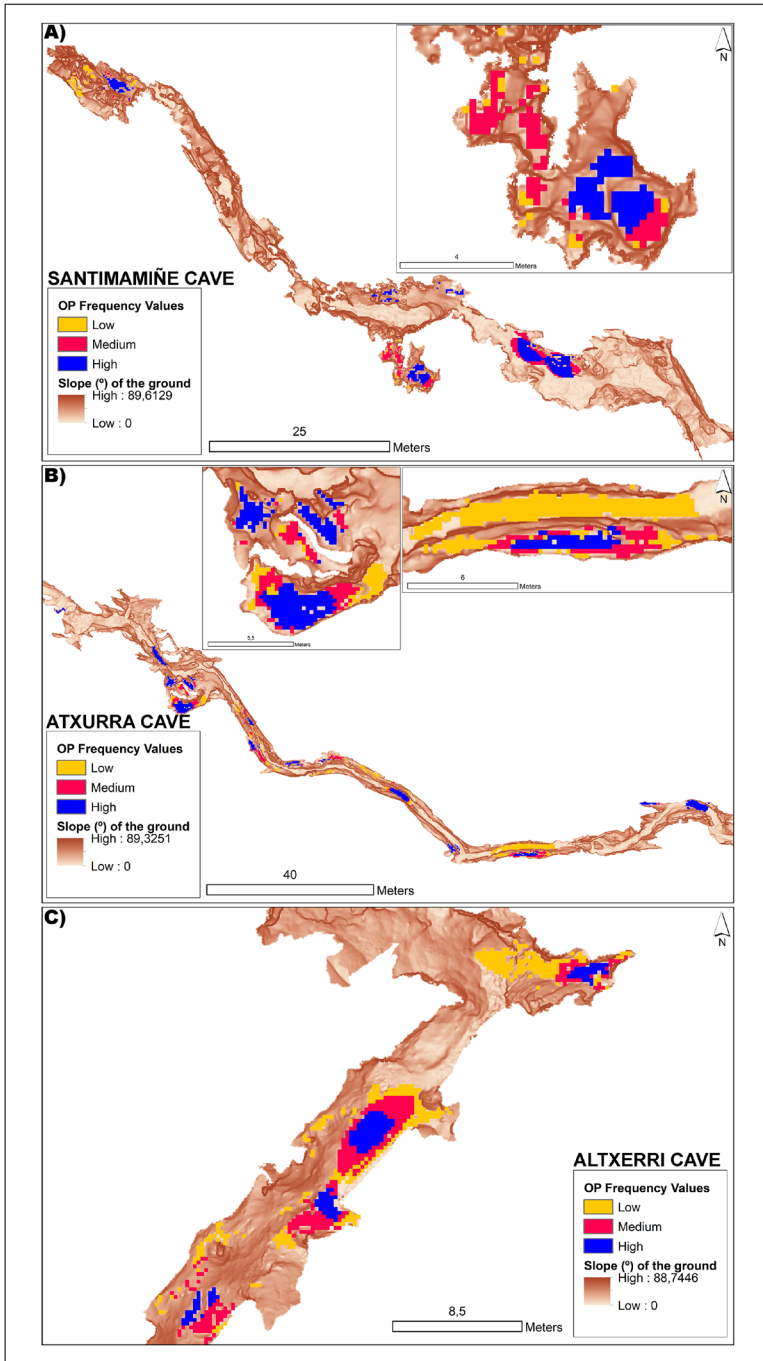
In this regard, we have identified cases in which the opposite appears to be true (small or unfinished figures placed on prominent surfaces). For example, in Sector J at Atxurra, there is a group of a dozen ibex that appears to have been positioned because of the high visibility (more than 66.66%) of the support. This contrasts with the small size of the figures, which would prevent them from being viewed from a distance.

Finally, we have compared the results using different lighting systems in our LOS analysis, to establish whether there is any major effect on the size of the illuminated space and, therefore, on the distance from which the decorated supports were visible. For example, in the paradigmatic case of the shelf in Sector J of Atxurra, the location of the hearths at the foot of the panel (radiocarbon dated to the same period as the artworks themselves) seems to have been determined to provide visibility, since the halo of light from the fire would have illuminated almost the entire panel (Garate *et al.*, 2020a, 2020b; Medina-Alcaide *et al.*, 2021), increasing the visibility rates of the figures on the right-hand side (see [Supplementary Materials](#)). This is even more outstanding because of the combination of techniques of two horses Atr.J.II.65 and 74. In any case, it is also necessary to take into account factors such as the smoke from the lighting tools (specifically in spaces with poor ventilation), which might alter the visibility rates (*e.g.* Kedar *et al.*, 2020; Salmon *et al.*, 2021). By contrast, reflectance would have further increase that viewshed (more or less 40%) but would not significantly change the visibility percentages of the panels. These insights should be confirmed or dismissed through further analysis (*e.g.* Jousteau *et al.*, 2020).

## Capacity

With regard to the results of the potential audience, we can confirm that in the caves analysed, the decorated places generally allowed for small capacities (with values of around 7–8 people, and in almost all cases less than 20) (Table 1). In any case, it should be noted that these are the maximum values, taking into account all the available space. It is important to bear in mind that if there were too many people in a space, one person would block the line of sight of other. Therefore, if they were to remain as comfortably as the depth of a cave allows and operate with relative





**Table 1** The potential audience in the caves analysed, and their estimated position. It should be noted that these are the maximum values: If they were to remain as comfortably as the depth of the cave allows, we should consider sufficiently reduced capacity figures (at least half the maximum value obtained). Low values (between 0 and 33.33%); medium values (33.33–66.66%); and high values (66.66–100%)

Sector	Squatting	Standing	Low	Medium	High	Max cap	Sector	Squatting	Standing	Low	Medium	High	Max cap
<i>Santimamiñe cave</i>													
San.1	7	23		11	19	30	Attr.A	1				1	1
San.2.1	1				1	1	Attr.Cf		6			6	6
San.2.2		2			2	2	Attr.C	3	4	1	2	4	7
San.3-4	2	11	2	6	5	13	Attr.Df	3	2		1	4	5
San.5	1	10	5	1	5	11	Attr.D	13	8	5	6	10	21
<i>Altverri cave</i>													
Alt.A.I	2	14	11	3	2	16	Attr.D'F		6	2	2	2	6
Alt.A.II.1-2-3	3	36	13	17	9	39	Attr.G	2	7	3	3	3	9
Alt.A.II.4-5	2	8	3	5	2	10	Attr.E'	2	1			3	3
							Attr.F'H	5	2	3	3	1	7
							Attr.G'G'fIf	2	14	8	1	7	16
							Attr.I	2	1			3	3
							Attr.JfJ	8	28	26	6	4	36
							Attr.J'f	2				2	2
							Attr.K'	1	10			11	11

flexibility of movement, we should consider sufficiently reduced capacity figures (at least half the maximum value obtained).

To allow comparisons between the different sectors, we have applied a single measure (the estimated radius of action of the prehistoric torches), and the results are therefore influenced by this selection. Nevertheless, in the large spaces (such as the large passages detected in the decorated Sector II.1 in Altzerri or J in Atxurra) the illuminated space (and therefore their capacity) would have been increased by employing diverse lighting systems. This would not have occurred in areas with limited or reduced spaces, in which more powerful lighting would not have extended the space from which the GUs were visible, as is the case with the “Antechamber” and the “Chamber” of Santimamiñe.

Having classified the usable space according to visibility, we can establish that in most cases, a large portion of the target audience would have high visibility values (between 66.66 and 100 percent of the GUs of the analysed sector) (Table 1). By contrast, there are other sites, such as Sector J in Atxurra, where potential observers would never have an overview of the panel, due to its large size (more than 14 m), and the partial concealment of some GUs because they are positioned on a ledge. This might prove that the intention was to highlight certain figures to be viewed from a greater distance and a larger audience, but limiting the potential capacity to the bulk of the ensemble.

## Discussion

If we consider Palaeolithic graphic activity as a (public or restricted) visual communication system, the location of the figures (especially in sets with a large number of GUs) should follow specific patterns that facilitate (or restrict) their visibility, or at least they should not be arranged chaotically in the caves. Of course, it is impossible to either determine or measure other psychosocial constraints (such as cultural proscriptions), which would greatly affect their final function and interpretation (Domingo *et al.*, 2020; Llobera, 2000). Furthermore, it is evident that some figures have been positioned in specific sites because the natural forms of the supports (volumes, reliefs, fissures) evoke animal shapes (*e.g.* Sauvet & Tosello, 1998; Sauvet & González-Pumariega, 2017; Sakamoto *et al.*, 2020).

Comparing the results obtained by the LOS and capacity analyses with other spatial factors (such as accessibility), we can see that in the cases studied (and chiefly in Santimamiñe and Atxurra), many of the sectors are located in hard-to-reach places. Others are easier to access, but in all cases, they are located in the deeper areas of the caves and tend to be of low capacity. In Atxurra, for example, almost all sectors are located out of the main transit route of the gallery, which runs through the low and flat area of the passage (Intxaurbe *et al.*, 2021). It is worth highlighting the paradigmatic case of Sector C, which can only be reached by a dangerous climb. Furthermore, an estimation of their viewsheds (confirmed by the LOS analysis) showed that these GUs were not visible from the main access path (Intxaurbe *et al.*, 2020). To these cases in Atxurra, one might add the “Antechamber” and “Chamber” of Santimamiñe and Sectors II.4 and II.5 of Altzerri. That is, there appears to be an

intention to hide—or at least physically restrict access to—some of these Magdalenian rock art ensembles, once again taking advantage of the morphology of the cave, as happens in other open-air contexts (*e.g.* Gillings, 2015). This intention would be confirmed by the reduced capacity of these places.

On the other hand, there appear to be other less compromised areas of access (albeit in deep and remote parts of the caves), where there does seem to be an intention to highlight some of the GUs from the main access routes. This is the case of a part of the GUs in Sector J in Atxurra and Panel II.1 in Altxerri, located on the same natural thoroughfare towards the back of the gallery. Other authors (González-Sainz, 2017) have mentioned similar cases nearby from these chronologies (*e.g.* the main panel of Ekain, located in an area of transit), whose morphology (in a narrow place between the wall and the ground) prevents it from being seen immediately, something similar to what would happen with large decorated walls, such as Sector J in Atxurra (with very few observation points affording a full view of the panel, all located in hazardous spaces with limited available space).

Finally, as previous authors have pointed out (Sieveking, 1997), it is remarkable how Magdalenian societies were encouraged to make figures in certain elevated places, despite the difficult access posed for artists, through without any additional risk for potential viewers, who could view them from a convenient location. For example, the small ibex in Sector J of Atxurra were visible from the main path through the gallery, but the Palaeolithic authors who drew them were fully exposed to falling. This also appears to be the case in other Magdalenian decorated caves, both nearby—*e.g.* the main panel of Armintxe, visible when accessed from a lower cave level (González-Sainz, 2017)—and more distant, such as the “Camarín” in Peña Candamo (Corchón *et al.*, 2017), the polychrome horse in Labastide (Simonet, 1999) and the “sorcier” of Trois-Frères (Bégouën *et al.*, 2014), but also in older chronologies (*e.g.* Chauvet, El Castillo, Pech-Merle, Lascaux or Cussac) (Delluc & Delluc, 1979b; Groenen & Groenen, 2019; Jouteau *et al.*, 2019a; Le Guillou, 2005; Lorblanchet, 1992).

Our initial observations suggest that different decoration patterns might exist within the same cave, but without following a random distribution (Breuil, 1952): (1) outstanding figures in high and dangerous areas but visible from the main paths through the caves; (2) figures placed in visible surfaces but only reachable after some accessibility difficulties; (3) hidden figures in narrow (and sometimes dangerous) places only visible to a few people at a time; and (4) GUs position on visible surfaces with no accessibility difficulties (this would be the case with some non-figurative motifs in the habitat site in Santimamiñe). This does not necessarily imply that the art has different meanings or functions according to its spatial organization; there could have been other cultural reasons that prevented or allowed its viewing (Llobera, 2000), confirmed by ethnoarchaeological approaches (Domingo *et al.*, 2020). However, these studies also seem to support the idea that the morphology of the rock shelter or cave can be used to prevent certain figures from being seen (*e.g.* as in Drupni site’s *Malinji* depiction) (Domingo *et al.*, 2020). In short, these analysed rock art sets appear to be organized depending on spatial features, by selecting certain natural canvases in these caves, based on their different levels of visibility, capacity and accessibility. This would mean that were underground exploration

activities in the caves prior to the graphic activity, which might have left some evidence in the archaeological record (Medina-Alcaide, 2020). In any case, even in the visually most enhanced examples (GUs located in the most prominent canvases), these ensembles appear to be targeted at a small and restricted audience (given the low/medium capacity of the decorated areas and the difficult access), who would only be able to view these figures by knowing their location in the deeper parts of the cave.

## Conclusions

The use of resources that compute spatial information is necessary in the study of Palaeolithic rock art in order to avoid subjective or biased perceptions, especially in the case of caves. This study describes a methodology capable of analysing the visibility of the canvases in decorated caves, as well as their capacity, through direct analysis of 3D models in GIS. Three caves with recent Magdalenian rock art (Atxurra, Santimamiñe and Altxerri) have been studied to assess their visual impact on a set of hypothetical observers inside the cave. For this purpose, we have taken into account the morphology of the three caves, selecting the places available (with flat surfaces) and measuring the height of the ceiling, in order to establish the hypothetical posture of artists and observers. Prior to the analysis, geomorphologic studies must be used to determine the changes that have occurred in the cave since the Magdalenian. The workflow has been summarised in a Python script for ArcGIS® to make it more accessible to other researchers and can therefore be easily replicated in other caves or edited to include new variables and values (*e.g.* psychological perceptibility, reflectance).

The results of our research show that in the three caves studied, some of the figures were executed in those parts of the natural supports that afford the greatest visibility. That is, these Palaeolithic societies arranged some of their graphic work in places where the possibility of being seen was greater, even if this involved risks for the artists due to difficulties of access. On the contrary, there are also other examples where there seems to have been an intention to conceal and physically limit their visibility, taking advantage of the particular morphology of some sites, such as niches or cornices. To this, we must add that the sites analysed are located in the deeper reaches of the caves (many of them in places of mostly complicated and dangerous access) and small maximum capacity (with only few exceptions). Other cultural factors, such as prohibitions, might condition these remarks, but they are difficult to determine. Even so, further objective analysis (*e.g.* statistics) is needed to determine whether there might be some form of correlation between the features of the GUs, such as their complexity (presence of details like eyes or pelage, degree of finish and combination of techniques) and dimension and spatial parameters such as visibility, capacity and accessibility.

In conclusion, the spatial organization appears to indicate that in the cases analysed—three caves with recent Magdalenian rock art in Northern Spain—we see a visual communication system with restricted and controlled access, albeit there may be other unknown cultural factors that we have failed to take into account. The GUs would be visible, making use of morphology to enhance them in some cases, only to those who knew their exact location inside the caves, and in any case, they could

not generally accommodate large audiences. Nevertheless, it has been demonstrated that these caves were submitted to an exhaustive underground exploration before a complex iconographical display was planned. The technical challenges such as the complete darkness, the long distances and the hostile orography were not sufficient to deter the symbolic motivations of Magdalenian societies.

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**Availability of Data and Material** <https://github.com/inakiintxaurbe/line-of-sight-and-potential-audience-analysis-to-cave-art>

**Code Availability** <https://github.com/inakiintxaurbe/lineof-sight-and-potential-audience-analysis-to-cave-art>

## Declarations

**Conflict of Interest** The authors declare no competing interests.

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